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MEC2540A-UK-11-23

Practical Electronics

Volume 53. No. 2
February 2024
ISSN 2632 573X

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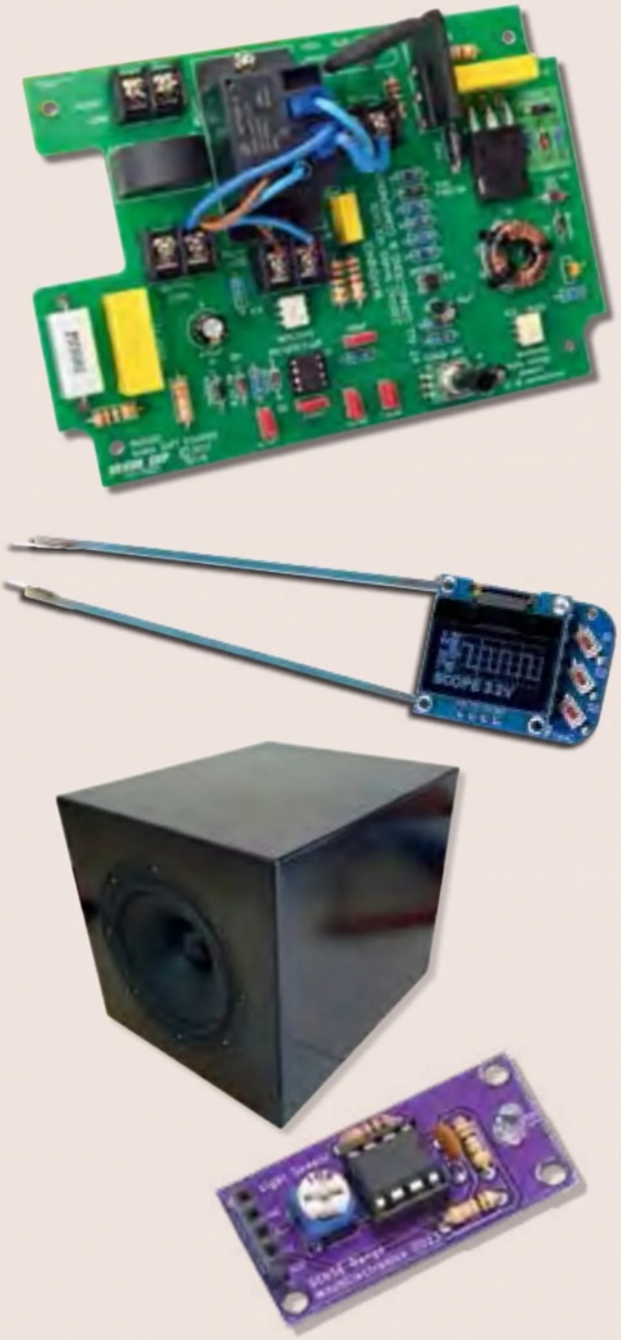

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Advanced SMD Test Tweezers – Part 1 by Tim Blythman 26
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Made in the UK.

Written in Britain, Australia, the US and Ireland.

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The March 2024 issue of *Practical Electronics* will be published on Thursday, 1 February 2024 – see page 72.

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by **LOUIS MEULSTEE**

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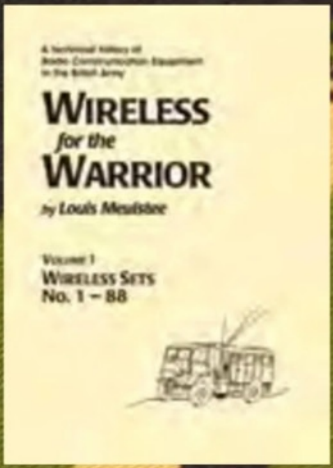

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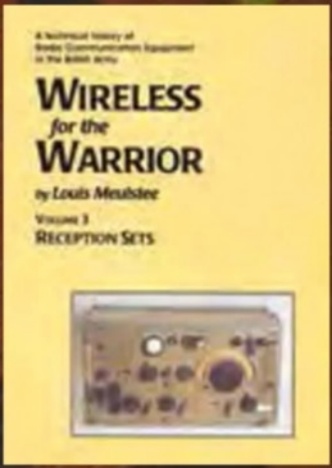

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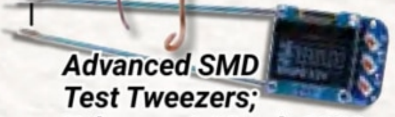
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Volume 53. No. 2
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Looking forward to 2024

By the time you read this it will be (a chilly) 2024, the start of a new year and a brand new batch of exciting projects and articles. Looking ahead, I can see a superb range of circuits and designs to suit every interest and level of experience.

The most popular area for readers is probably audio and Hi-Fi. In addition to Jake Rothman's uniquely insightful *Audio Out* column, we have some mouth-watering amplifiers coming down the line for you to build and enjoy. Plus, for speaker enthusiasts, there will be an innovative *Loudspeaker Test Jig* that uses your computer's sound card to measure loudspeaker performance, inductors, capacitors and complex impedances. With this *Jig* and appropriate software, measuring and tweaking crossovers, cabinets and speakers is easy.

For testbench fans we will be using a Raspberry Pi Pico W as a substitute for GPS modules for when you can't get a reliable GPS signal. It enables you to get time from an internet NTP server via Wi-Fi and is accurate to a fraction of a second. Need a basic signal generator that's compact, cheap to build and doesn't involve many parts? We've got you covered with a design that goes from 10Hz up to 25MHz. Plus, there will also be a handy device that can provide test voltages, test signals, vary a resistance, switch a component in or out of circuit and even measure some voltages. A veritable *Swiss Army Knife* of test and measurement options.

Teach-In is back!

The really exciting news for the new year is that Mike Tooley's *Teach-In* series is returning. For 2024, Mike has chosen the ESP32 device as the heart of an excellent series of in-depth articles.

The ESP32 is a popular, flexible and powerful low-cost, low-power system on a chip microcontroller with integrated Wi-Fi and dual-mode Bluetooth. Mike will use this module as a basis for learning electronics and coding. He will be making no assumptions about your coding ability or previous experience of electronics. If you know one but not the other, then this will be the *Teach-In* for you. Even if you're a complete newbie you'll find Mike's hands-on approach the perfect route to learning.

From all of us at *Practical Electronics*, thank you for your support over 2023, and we look forward to inspiring and informing you in all things electronics in 2024!

Matt Pulzer
Publisher

Cheeky chiplets

Techno Talk

Max the Magnificent

Instead of a single humongous silicon chip, tomorrow's devices may involve multiple chiplets in the form of optical chiplets, libraries of chiplets, die-to-die (D2D) interconnect, and network on chip (NoC) technology. A chiplet-based future is closer than you think.

It's not so long ago that the designers of digital integrated circuits (a.k.a. 'silicon chips' or just 'chips') employed the terms SSI, MSI, LSI, VLSI, and ULSI to represent Small-, Medium-, Large-, Very-Large-, and Ultra-Large-Scale Integration, respectively. By one convention, the number of primitive gates represented by these terms were: SSI (1-12), MSI (13-99), LSI (100-999), VLSI (1,000-999,999), and ULSI (1,000,000 or more).

In order to 'compare apples to apples,' we also used to talk in terms of the number of 'equivalent gates' on a chip. Most designers – excluding those working with emitter-coupled logic (ECL) – adopted the convention that an equivalent gate was represented by a 2-input NAND gate, which equates to four transistors in a CMOS chip.

I find it interesting that the huge number of gates and transistors that can be implemented on today's chips has rendered such fine distinctions moot. As a result, terms suggesting greater than VLSI levels of integration are no longer in widespread use.

How big? How many?

In my previous *Techno Talk* column (*PE*, January 2024), we touched on the topic of 'technology nodes' (a.k.a. 'process technologies,' 'process nodes,' or just 'nodes'), which refers to specific semiconductor manufacturing processes. One way to think about this is that the number associated with a process node represents the size of the smallest physical structure that can be created in or on the surface of the chip. Thus, a 1µm node can have features – like the width of tracks, for example – of one millionth of a meter in size.

The smaller the features, the greater the number of transistors that can be squeezed into the same area. For example, Apple's latest and greatest A17 Pro processor, which is implemented at the 3nm node (where 1nm is one *billionth* of a meter), boasts over 19 billion transistors (my eyes are watering just thinking about this number).

The problem is that we are reaching the maximum physical size of chips that can be constructed using today's extreme ultraviolet (EUV) lithographic technologies. The practical limit is around 25mm × 25mm = 625mm^2 (roughly a square inch). It is possible to create larger devices up to around 29mm × 29mm = 840mm^2, but the yield (good chips vs. bad chips) quickly falls to unacceptable (unprofitable) levels.

The 'problem' is that we have an insatiable desire for more and more transistors. Artificial intelligence (AI) and machine learning (ML) applications are sprouting like mushrooms. Also, they are migrating out of the cloud (in the form of data centers) to the Edge, which is where the internet meets the real world.

So, what's the solution? I'm glad you asked. The industry is currently buzzing with excitement over the latest developments in…

Cheeky chiplets

The technical term for a semiconductor chip is 'die' (plural 'dice'). The solution to our capacity conundrum is to implement a large design across multiple dice, mount them on a common substrate (base), and present everything in a single package. In this case, the dice are commonly referred to as 'chiplets' or 'tiles,' the packaged product is referred to as a 'multi-die system,' and the substrate is typically a silicon interposer, although organic substrates (special printed circuit boards) are also a possibility.

There are four main chiplet use cases. One is to scale things up by mounting multiple homogeneous (identical) chiplets (think multiple processing units) on the substrate. Another is to take a design that is too big to fit on a single die, and to split that design into two or more chiplets. A third use case is to take functions like transceivers that have already been proven at one technology node and implement them as chiplets that support the main die. The fourth scenario is to disaggregate everything into heterogeneous (dissimilar) dice, each being implemented at the best node (in terms of cost, power, and so on) for its function.

Today's chiplet outliers

Until recently, the only companies using chiplet technology have been outliers like the folks at Intel who control every aspect of the fabrication process. In the case of Intel's Agilex 7 FPGAs, for example, the main die is supported by two to six transceiver (XCVR) chiplets.

Another Intel example is provided by their Data Center GPU Max Series of devices (these used to be known as Ponte Vecchio GPUs). These bodacious beauties boast 47 chiplets and 100+ billion transistors. 'O-M-Goodness gracious me,' is all I can say.

Chiplets for the unwashed masses

The way digital logic designers create today's system-on-chip (SoC) devices is as a collection of 'soft' intellectual property (IP) blocks. Many of these IP blocks are provided by trusted third-party vendors because there's no point in reinventing the wheel (in the form of a processor core or a USB interface, for example). The designers also create their own 'secret sauce' IPs that will differentiate this device from its competitors. These IPs are represented at the register transfer level (RTL) of abstraction, and all the IP descriptions are compiled (synthesised) into the final gate-level chip design.

The dream is to be able to create tomorrow's multi-die systems as a collection of 'hard' IP blocks in the form of chiplets. In this case, some chiplets would come from trusted third-party vendors while others would be developed in-house.

If you'd asked me when this would come to be six months ago, I would have guessed it to be five or more years in our future. Since then, I've been talking to companies like Ayar Labs (optical interconnect chiplets), Arteris (network on chip (NoC) technology), YorChip and Zero ASIC (both offering libraries of chiplets), and Eliyan (die-to-die interconnect). I'm also looking forward to the forthcoming Chiplet Summit, which will be held 6-8 February 2024 at the Santa Clara Convention center. This will be the place for chiplet companies to 'see and be seen.' All I can say is that I now think our chiplet-based future is a lot closer than I'd previously thunk.

Win a Microchip PIC-IoT WG Development Board

Practical Electronics is offering its readers the chance to win a Microchip PIC-IoT WG Development Board (AC164164) – and even if you don't win, receive a 15%-off voucher, plus free shipping for one of these products.

The PIC-IoT WG Development Board combines a powerful PIC24FJ128GA705 MCU, an ATECC608A CryptoAuthentication secure element IC and the fully certified ATWINC1510 Wi-Fi network controller, which provides the most simple and effective way to connect your embedded application to the Google Cloud IoT Core. The board also includes an on-board debugger, and requires no external hardware to program and debug the MCU.

The PIC24FJ128GA705 16-bit microcontroller features up to 128KB of ECC Flash, 16KB of RAM and eXtreme Low Power. It has a 12-bit ADC running at 200ksps with up to 14 analogue inputs, 3 comparators and CTMU for touch applications. Available in 28-pin, 44-pin and 48-pin packages, this family is ideally suited for general-purpose applications.

Out of the box, the MCU comes preloaded with firmware that enables you to quickly connect and send data to the Google Cloud Platform using the on-board temperature and light sensors. Once you are ready to build your own custom design, you can easily generate code using the free software libraries in MPLAB Code Configurator (MCC).

Worth $39.50 (approx £31.99) each

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Net Work

Alan Winstanley

This month's column proves how power supply glitches can catch out even seasoned home network users, suggests some cheap and cheerful workshop tools available direct from China, and there's a quick roundup of space news as well.

Recent Net Work columns have described some power supply considerations for home technology users, suggesting some small uninterruptible PSUs that would keep peripherals running during power failures, and I also unravelled the multi-dimensional mysteries of DC power connector plugs.

A recent problem in my home office reminded me not to take everything for granted. My Brother-branded P-Touch label printer has an LCD display problem (missing pixels), but was it the LCD itself or the main board that was causing this? I gambled £15 on an old labeller being sold on eBay for spares or repairs. After swapping the LCD I still had the same problem and the donor main board was no good either, so the hunt for spare parts continues. In addition, the label printer uses a 9.5V power brick with a unique feature: unlike every other mains adaptor I've ever come across, its DC connector is *centre-negative*, but this is unlabelled, so the printer could well have been ruined altogether if I'd tried an ordinary 9V adaptor on the bench without double-checking the polarity first. A simple polarity tester made by Minwa (part no. MW 229) is sold online that checks the supply at a glance.

Positive ID: this simple polarity checker by Minwa is handy for quick installation checks on DC leads, CCTV supplies, mains adaptors...

Probably my all-time favourite piece of home network equipment is a Synology network attached storage (NAS), which hosts twin hard disks offering RAID-like backup security, and it's also fitted with gigabit Ethernet and three USB ports, so I use it as a Windows network printer server as well. Being DLNA-compatible I can stream multimedia onto a smart TV and network media player, and a handy Android app helps with server file management. I find its slick and thoughtfully designed software is almost sublime in places and, unbelievably these days, although the NAS is over 12 years old it is still going strong and supported by Synology, something I would soon come to appreciate, as I'll describe next.

Going for broke: the author's Synology NAS server (yellow status LED) warned of a 'degraded volume' after some power cuts.

A NASty surprise

I've been trialling a 12V mains adaptor-style UPS and a multi-voltage compact type on my home office network, as shown in *Net Work*, December 2023. I had a sticky note on my busy desktop reminding me to consider UPS protection for the Synology NAS sometime as well. Then, just a few days before I penned this month's column, the mains electricity supply failed at midnight without warning. The 'juice' was then restored before flashing on and off again at least half a dozen times over the following half hour. Happily, the 9V and 12V UPS supplies powered the modem and router without complaint, but after 30 minutes of disruption I heard a forlorn beeping sound emanating from the Synology NAS. An ominous flashing amber LED warned of a 'degraded volume', as Synology's

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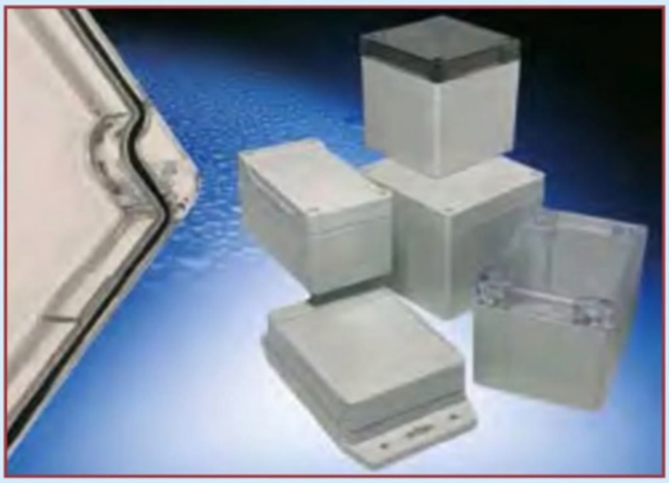


online resources explained. In other words, the repeated power cycling had corrupted a hard drive or maybe crashed it completely. If so, hopefully the NAS had done its job, as data would still be intact on the other disk, I prayed, though a total hardware failure could not be ruled out.

I found data was still accessible over the network, a promising sign that one disk was still functioning. Something I've learned the hard way over the years is that if a disk drive is still working under these circumstances, it's wise not to power it down in case it doesn't boot up again, so it's best to keep it spinning. Synology's online resources and its user-friendly software made the job of troubleshooting easier, especially at two o'clock in the morning! Error messages confirmed that one 1TB disk was down, although its condition was described as 'healthy' and the other disk was spinning as normal. There were options to 'repair' the damaged data but they advised replacing the degraded drive, which is what I chose to do rather than risk a total data loss. A welcome touch was Synology's 'Locate disk' feature that flashed the dodgy disk's LED to make sure the correct drive is swapped out, guided by their commendably clear online instructions.

Hard disks are graded for performance by the end-user's application, eg for everyday desktop PCs, always-on NAS use or constantly thrashed surveillance systems. I again chose Western Digital's 'Red' NAS drives, but the minimum capacity I could find had increased to 2TB, so I needed to upgrade both disks at a cost of £175. This just goes to show that power outages can hit anybody – the rigmarole was an expensive and time-consuming problem to sort out.

To round off the subject, although the NAS has a 12V 5A laptop-style power brick, the spec. sheet quotes power consumption of just 25W (1TB disks, 10W idle). Since a lead-acid UPS would be too big and costly for this always-on application, I've ordered another iPower-DC^2 UPS (see previous columns) to go between the mains adaptor and the NAS. This multi-voltage (9V / 12V/ 24V) UPS promises up to 2.5A at 12V (30W) for at least 30 minutes of backup. The UPS consumes 6W itself, making 36W in total, so the mains adaptor should be rated accordingly. I'm reaching some limits here, so I've built a DC lead 'breakout box' in a small Hammond enclosure allowing me to check the current with a multimeter – assuming I can sort out those DC connectors!

Readers might be interested in the manufacturer's data sheet at: **https://bit.ly/pe-feb24-power1** and a block schematic of the UPS with some very interesting design notes is at: **https://bit.ly/pe-feb24-power2**

Note that previously published URLs linking to these products have since been updated by the manufacturer, and are shown in my blog at: **electronpublishing.com**

Spoilt for choice

These days, many readers source products directly from China and the range of merchandise sold by the likes of AliExpress and Temu is dizzying. One thing that's undeniable is the tempting pricing, and a discerning hobbyist who knows what he's looking for, and doesn't mind a little bit of a gamble, can often bag a bargain. It seems as if AliExpress and Temu are slugging it out for trade, and I discovered that, if you can accept a few oddities or rough edges here or there, AliExpress offers some interesting-looking and unusual tools and equipment at almost silly, giveaway prices that will help constructors to get more out of their hobby.

One example that recently landed on my doormat was a combined desoldering iron and suction pump, branded the Yihua 929-D, which cost about £10 delivered to the UK. This 30W iron has a hollow point allowing molten solder to be drawn up into the pump and it's proved perfectly acceptable, making short, one-handed work of desoldering some PCB pin headers provided care is taken not to 'fry' the board. The PVC flex can get in the way due to its shape memory, which makes for quite a wrestling match at times, and it's also fitted with an EU 2-pin Europlug (similar to a UK shaver plug), which is nothing that an EU travel adaptor doesn't cure. Even so, it's been a useful time saver and a handy addition to the toolbox. A 110V version is sold for the US, and kits of different diameter hollow tips are also available for just a pound or two. Models incorporating an electric vacuum pump are also sold, from about £20. While you're at it, why not treat yourself to a heat-resistant silicone benchtop work mat as well (£3.15).

Other budget-priced handy tools I spotted online include a 'plastic welder'. These are designed to 'hot-staple' damaged plastic products such as car bumpers back together, or plastic bins or boxes (including, in my case, the large bin of my office shredder). As certain thermoplastics like nylon, polypropylene (PP) and high-density polyethylene (HDPE) can't be glued, hot-stapling them could be the answer. A cheap and cheerful 'welding gun' (like the old Weller 100W solder guns) carries a metal staple (several styles are available) which heats up in seconds and it can then be melted into the plastic. Don't overdo it but hold it steady and allow it to cool, and the gun can then be removed leaving the plastic 'stitched' together. The wires ends can be snipped off and, depending on the type of plastic, the repair can be dressed and filled if necessary. A 50W welding gun and kit only costs about £10-£12 imported direct from China, and spare staples are in plentiful supply. It could easily pay for itself in just one repair job. They will also be found on eBay.

As constructors doubtless know, when stripping the ends from multistranded wire, stray copper whiskers can be a

YIHUA
2 IN 1
Electric Desoldering Iron
Tin Sucker

The Yihua 929-D is a 30W desoldering iron and suction pump, costing just £10. EU and US voltages available. (AliExpress)

A 'plastic welder' uses hot staples to melt and stitch 'unglue-able' plastic panels and parts back together again. It could easily pay for itself after one job. (AliExpress)

This complete wire ferrule crimping kit includes a lifetime's worth of ferrules for under £10. (AliExpress)

The popular 858D hot air reworking tool is designed for working with surface-mount devices or heatshrinking, among other applications. (AliExpress)

menace as they can short to neighbouring terminals or the chassis. Wire ferrules are used to dress the ends of such wires neatly, and I noticed AliExpress lists a complete ferrule crimping kit including 1,200 ferrules for just £5.61 plus shipping and tax. Search for 'Crimping Pliers HSC8 6-4A Tubular Terminal Crimper'. Ratchet-type tools are sold for car-type blade crimp terminals, eg 'SN Series Crimping Pliers SN-48BS' for just £7.39 + taxes etc. At these sort of prices, not many will mind adding them to an order to make up a postage-free order value, as they might come in useful one day.

A lot of hot air

With the advent of surface-mount devices and the need to service equipment such as smartphones or laptops, another useful soldering tool for a busy workbench is a hot air reworking tool. These can simultaneously melt larger areas of surface mount joints to enable BGA chips or components to be replaced. For hobbyist users, the popular '858D' type is ridiculously cheap on AliExpress, and many clones are available from £22 + tax. The temperature and fan speed are variable and different size nozzles can be fitted. Some models include a soldering iron, and spare exhaust fans and handles can be had for pocket money prices.

If the idea of making your own battery packs appeals, then small but powerful welders are sold that will spot-weld nickel strips into place on, say, 18650-type rechargeable cells. Small units start at about £20 and I sourced a compact handheld one with an OLED display, for under £40. They are USB rechargeable and produce quite an alarming kick that belies their small size. Strangely, the term 'gear' is commonly used to describe power levels; 'gear adjustment' can offer, say, '30 gears' of energy. The necessary nickel strip for welding connections together is sold separately in various gauges.

These devices are emphatically not for casual workers or the faint-hearted and, because of the variables involved, individual spot-welds can sometimes be hit or miss. Without exception, extreme care must be taken to safeguard against glare or 'welder's arc eye' – I speak from experience after administering first aid (special eyedrops) to save a welder's eyesight in years gone by. As these devices sometimes belch out a big, fat spark, metal spatter is another hazard: it will damage plastic spectacle lenses as well as your eyesight, so suitable welding-grade tinted safety spectacles or googles have to be worn. I noticed that some models now have a foot pedal control too, which is a good idea.

A very compact but powerful spot welder is used for making up battery packs using nickel strip. This model has an OLED display. Tinted welding safety spectacles are absolutely essential.

If you're looking to add to your workshop toolkit, plenty of choice is available at budget prices but when ordering, keep an eye out for added sales tax and postage costs, remembering that delivery can sometimes take many weeks. You can sign up for an account at: **aliexpress.com**

Back in the workshop

I've written before about the rise in popularity of rechargeable power tools, with Ryobi's range of mid-range, mid-priced One+ 18V tools expanding all the time; they've been used in my workshop for nearly 20 years. The 18V batteries and chargers are bought separately for use on 'bare' tools, and in the US more than 250 tools are now available, although the choice in Europe is more limited.

For smaller soldering jobs I've abandoned gas-powered soldering irons altogether – these temperamental and unwieldy, fire-breathing tools vent lots of hot air making it too easy to cause collateral damage. For quick soldering tasks I now bring out Ryobi's 18V One+ cordless soldering iron, which performs decently enough on the bench. It's well balanced and the battery charge lasts a reasonable time but the choice of bits supplied is very limited – just a conical type and an oversized 5mm chisel

Ryobi's R18-RT rotary tool uses a One+ 18V battery and its flexible drive provides variable speed operation of mini tools for crafters and hobbyists.

No-brainer: Aitana Lopez is an entirely AI- and Photoshop-generated 'influencer' who has gained more than 120,000 'followers'.

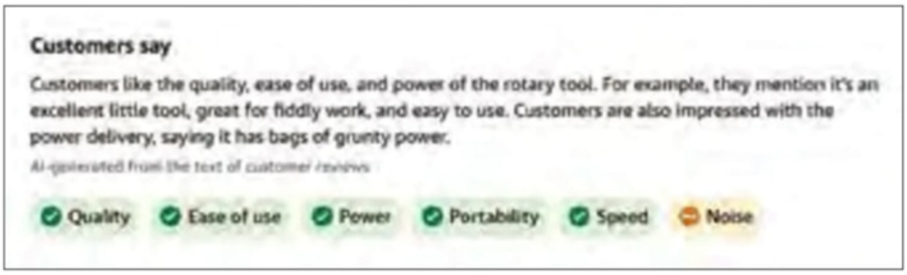
blade. I'm currently investigating some compatible types.

Another recent arrival was Ryobi's cordless multifunction Rotary Tool (R18-RT) which has a variable benchtop speed controller and 90cm flexible drive shaft. A One+ 18V battery powers the 4,000 – 35,000 rpm motor and the workstation offers the usual mini-style grinding, engraving, sculpting, slicing, sanding and polishing actions, although for more demanding work I still revert to my mains-powered, Bosch-owned Dremel instead (and I've burnt out several of those, as well). Last, a handy Ryobi USB adaptor is available that converts an 18V battery into a USB powerbank. Although they have a built-in rundown timer, I've modified one to add a strangely omitted 'power on' LED; construction details are on my online blog. The full Ryobi One+ range is readily available in DIY stores or online, but prices vary so it pays to shop around.

Artificial influencers

It's rare that a day passes by without the term 'AI' cropping up in the news. This overblown buzzword has captured mainstream culture and examples of 'AI' are cited everywhere. Artificial intelligence boils down to machines and software simply doing the job that humans have pre-programmed them to do. AI chatbots such as ChatGPT can converse in a way that's indistinguishable from human interaction, and deep-fake videos are surfacing that contain frighteningly realistic, AI-generated *dramatis personae*. I once quipped that, at the rate things are going, one day there would be computer-generated movie stars or pop idols, and they might even have their own fan club. That's exactly what has happened: a Spanish agency called 'The Clueless' has created a sassy AI/Photoshopped 'influencer' character called Aitana Lopez who, according to Euronews – **http://tinyurl.com/44phc7m4** – has garnered over 120,000 Instagram followers. She has even been asked out for a date by an unknowing admirer. Aitana earns the agency upwards of €3,000 a month as a 'presenter' and such is her success that a second AI star called Maia Lima is now on the payroll as well. You can see Aitana's portfolio (NSFW) at: **https://bit.ly/pe-feb24-aitana**

Microsoft's Copilot AI-powered assistant is now installed firmly in its Edge browser and Bing search, and it does admittedly make a refreshing change from mindlessly trawling through classic search results. As they state: 'Microsoft Copilot is powered by AI, so surprises and mistakes are possible.' Both Amazon and eBay are keen to harness AI as well: Amazon now generates AI-powered product reviews that try to summarise an item's pros and cons, based on user feedback. When listing an item for sale, I noticed that eBay now offers an AI-generated product description as a starting point for sellers to modify further.



Customers say

Customers like the quality, ease of use, and power of the rotary tool. For example, they mention it's an excellent little tool, great for fiddly work, and easy to use. Customers are also impressed with the power delivery, saying it has bags of grunty power.

AI-generated from the text of customer reviews

Amazon now uses AI to create balanced product reviews derived from user feedback.

Space news

Regular readers will recall the sad demise of Virgin Orbit's ambitions to offer a 747-based satellite launching service that would have flown from an ordinary runway instead of needing a vertical launchpad. A make-or-break flight of the 'Cosmic Girl' 747 from Cornwall in England last year failed to deploy its payload and the company subsequently collapsed. Cosmic Girl lives on, however – the aircraft has now been acquired by Stratolaunch, a Californian-based air launch company, where she is now known as 'Spirit of Mojave'. (If you use an aircraft tracker such as **flightradar24.com**, the 747's registration is N744VG.) The firm is also developing the world's largest aircraft, a twin-fuselage six-engine 'Roc' launcher vehicle originally intended to launch customer payloads into space, but there are now major ambitions to launch hypersonic vehicles as well. Incidentally, the port-side cockpit is a dummy and is known as the 'mockpit'. More details at: **www.stratolaunch.com**

The first commercial runway-landing spaceplane to be built by the private sector is now complete and is soon to undergo trials at NASA. The Dream Chaser space vehicle (see *Net Work*, August 2023) is named 'Tenacity' and has been built by Sierra Space to provide at least seven flights to the international space station. An orbiting three-storey space habitat pod called LIFE is at the design concept stage, and would be the first commercial space structure of its type. A proposed 'Orbital

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The Dream Chaser spaceplane 'Tenacity' is undergoing testing with NASA and is destined to service the international space station.

Reef' space station hosting multiple pods is described as a 'mixed-use space station in low Earth orbit for commerce, research and tourism' and is promised by the end of this decade. You can learn more at: **https://bit.ly/pe-feb24-sierra**

Amazon's launch of two test satellites for its Kuiper program proved successful with all systems meeting or exceeding expectations, they say. Two-way video calling and 4K video streaming were demonstrated. Mass production of Kuiper satellites has begun and beta testing will be offered to selected customers later in 2024. Kuiper has signed up SpaceX, among others, to deploy satellites and they have also commissioned rides on Europe's long-overdue new Ariane 6. The heavy lifter's first mission won't be until the end of 2024; until then, Europe lacks any independent access to space.

Returning to last month's Ecowitt weather station topic, out of interest I tested a wire-ended WN30 temperature probe on a deep freezer last month and the screenshot of the mobile app shows how it fell from +19.4°C to −18°C and then clearly recorded the cycling of the fridge compressor (and me opening the door). Data is also uploaded to the Ecowitt cloud server.

Finally this month, while surfing around I stumbled across a USB dongle with a difference: far from being a benign flash drive, it contains a voltage-doubler circuit and a bank of capacitors that are designed to test (and/or destroy) a USB host by injecting high 'killer' voltages onto the data bus. I'm highlighting this to make readers aware of the 'USBkill' dongle, a device intended to stress-test hardware. It contains a rechargeable battery and can be operated wirelessly to 'test' laptops, smartphones, smart TVs, monitors, iPhones and more, and it can easily destroy vulnerable electronics in their entirety. Some bad actors are fabricating similar devices themselves, which is one more reason not to plug untrusted dongles into your hardware. You can see it in action at: **https://youtu.be/I6bRoSK39io**

That's all for this month's *Net Work*. Don't forget to visit the online summary where the above links are ready-made for you at: **electronpublishing.com**

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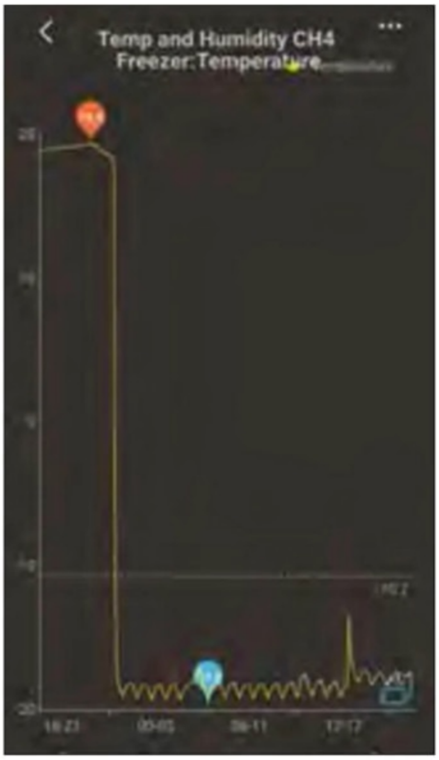


Screenshot of the temperature data captured by an Ecowitt WN30 wire-ended probe, tested on a deep freezer.

The Stratolaunch 'Roc' is the world's largest aircraft, and will air-launch payloads including hypersonic craft.

ACTIVE MAINS Soft Starter

PART ONE BY JOHN CLARKE

High startup current appliances can be dangerous, damage your work, cause brownouts or trip out the circuit breaker when power is first applied. This Soft Starter prevents the high surge current, replacing it with a slow current build-up and reducing the 'kick' you get from many tools.

Have you ever used a power tool that rips out of your hand when power is first applied? Or do you have a bank of computers or audio equipment (or similar) that you want to power up together from a single power point? When you do so, sometimes the circuit breaker trips, forcing you to go to the switchboard and reset it.

Tools with a motor that are powered from the mains, such as circular saws, hand grinders or routers can make a sudden movement as the torque from the motor startup rotates the tool. This can cause the tool to move dangerously. In the case of a saw, drill or router, it could move the cutting piece off position and possibly damage your work.

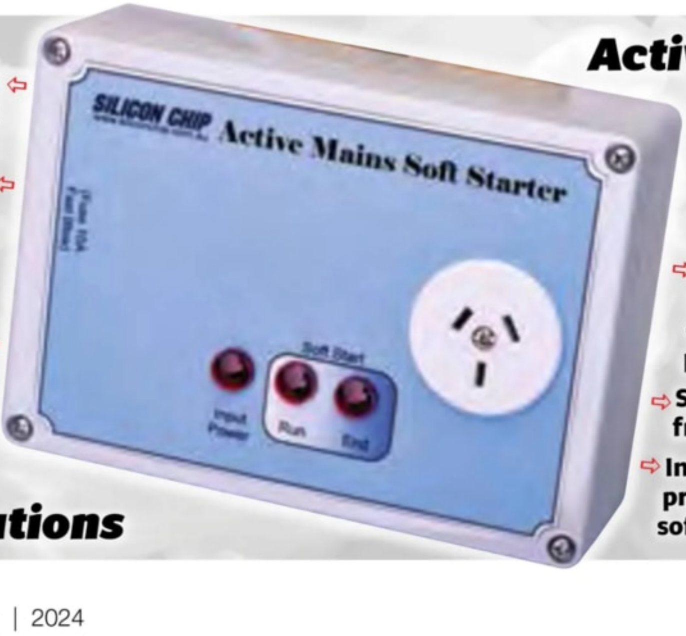
You might also hear a nasty 'splat' from the switch or plug when the equipment is powered up, indicating that it is being worn out by handling the high inrush current. All of that can be solved with a soft starter like this one.

As well as large motors, a high inrush current can be caused by the appliance or appliances using a toroidal

Active Soft Starter

Features and Specifications

- Suitable for fixed or portable power tools rated up to 750W
- Also suits large amplifiers, computers or other equipment with a high inrush current
- 10A continuous rating
- Uses trailing-edge phase control
- Switch on at mains socket/GPO or equipment power switch, including triggers
- Relay contacts bypass soft start circuitry at completion for minimal power loss
- Six startup rate options from half a second to 10s
- Indicators for power presence, soft starting and soft start end



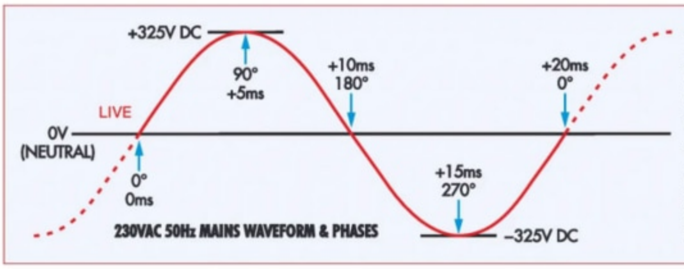


Fig.1: the mains waveform is a 50Hz sinewave with a positive voltage half the time and a negative voltage the rest of the time.

transformer or a switch-mode supply that rectifies the mains supply into a large capacitor or capacitor bank. The capacitance represents a near short circuit when power is first applied, causing a massive surge current.

This new *Active Mains Soft Starter* significantly reduces startup current, solving that problem. It's designed for devices that might be restarted frequently (like power tools), and its effect will not diminish, nor will it overheat with multiple restarts if used with equipment within its ratings.

You can use the *Soft Starter* with motorised tools up to 750W and appliances with substantial capacitance.

Two ways to use it

One way to use the *Soft Starter* is to have the appliance already plugged into the *Soft Starter* and switched on. You then switch on power at the mains socket/GPO (general purpose outlet). That is ideal if you want to power up several appliances together from one power point.

In this case, the soft start process begins at power-up (if an appliance is connected). Once the soft starting is completed, it supplies the full mains voltage until it is switched off at the power point.

The second method of using the *Soft Starter* is to have it powered up via the power point (GPO), then switch the appliance on and off with its own switch. This method is ideal when using power tools.

For both methods, the *Soft Starter* detects when the appliance is switched on and off by monitoring its load current. Soft starting only begins when current flow is detected. When the appliance is switched off, current flow ceases, and the power to the tool is also switched off, ready for another soft start.

750W rating

We tested the *Soft Starter* with various loads and power tools and found that it worked well for tools up to 750W. Some parts got uncomfortably hot when used with tools that draw more than that. Also, the ratings of some of the devices used are only sufficient up to that power level.

This is less of a concern when switching equipment like computers and amplifiers, as their inrush current periods are short. In that case, you can comfortably connect up to 10A (2.3kW) of equipment to the output.

For power tools above the 750W rating, consider building our *Refined Full-Wave Motor Speed Controller* that incorporates soft starting (June 2022). It is rated to handle 10A and therefore should handle any power tool that plugs into a standard mains socket/GPO. You could leave it set to full speed all the time and just use its soft-starting feature.

Presentation

The Active *Soft Starter* is housed in a compact plastic case with an IEC mains input connector at one end and a socket for the appliance. There are three neon indicators on the top. One shows when input power is applied; the second shows the slow voltage rise to the appliance, while the third lights when the soft start period has ended.

The neons are very sensitive and light up with a minimal current applied, so they don't show the full extent of the soft starting. However, they help to show what the device is doing.

Soft starting methods

The standard method to reduce the surge current is to add resistance in series with the mains supply, reducing the maximum current.

We previously published two *Soft Starters* using that method, one in April 2013 and the other in July 2013.

Both utilised negative temperature coefficient (NTC) thermistors. These devices act as a resistor that reduces its resistance as it heats up from the current flow through it. As it starts cold, the resistance is high, so the current is restricted. Then as the thermistor heats up, the resistance drops and allows more current to flow.

In both designs, after some time, the thermistor is bypassed by a relay to provide the full mains supply to the appliance. Bypassing the thermistor after the soft start prevents further heating of the thermistor, allowing it to cool down and be ready to provide another soft start when required.

Still, if the appliance is powered up repeatedly at close intervals, the thermistor does not have time to cool between uses, so its resistance can be quite low on successive starts. This means that the soft starting is not as effective in such cases.

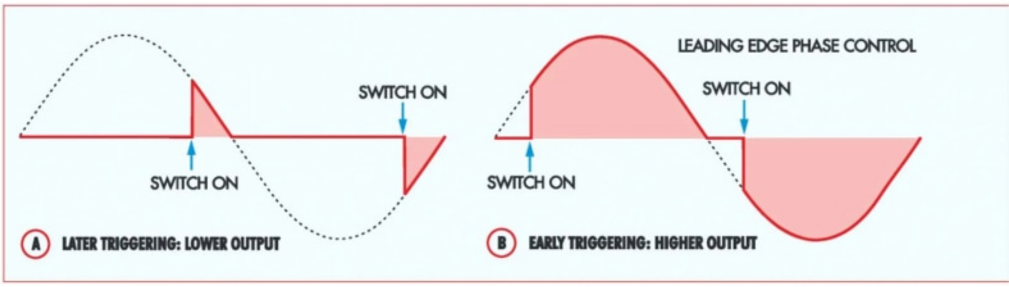
Another consideration is whether the NTC thermistor can survive long-term use conducting current for an appliance that draws significant current at switch-on. If power is switched on at the maximum voltage point in the mains waveform, the initial current can be extremely high, especially if the thermistor is still hot. Over time, that can damage and possibly destroy the device.

While our new *Soft Starter* does use a thermistor, it also includes phase control that initially applies a small portion of the mains waveform. The proportion of the mains waveform applied to the load increases slowly until the full mains cycle is applied. A relay contact then closes to bypass the soft start circuitry.

In doing so, it causes very little heating in the thermistor, so repeated starts are not a problem, and the device is very reliable.

Also, the phase control always starts at the beginning of the mains cycle, when the mains voltage is close to 0V. The control scheme used is called

Fig.2: traditional leading-edge phase control varies the switch-on point during the mains cycle but always switches off at the zero crossing. So the earlier it switches on, the more power is applied to the load.


LEADING EDGE PHASE CONTROL
SWITCH ON
SWITCH ON
SWITCH ON
SWITCH ON
A
LATER TRIGGERING: LOWER OUTPUT
B
EARLY TRIGGERING: HIGHER OUTPUT

...continued opposite

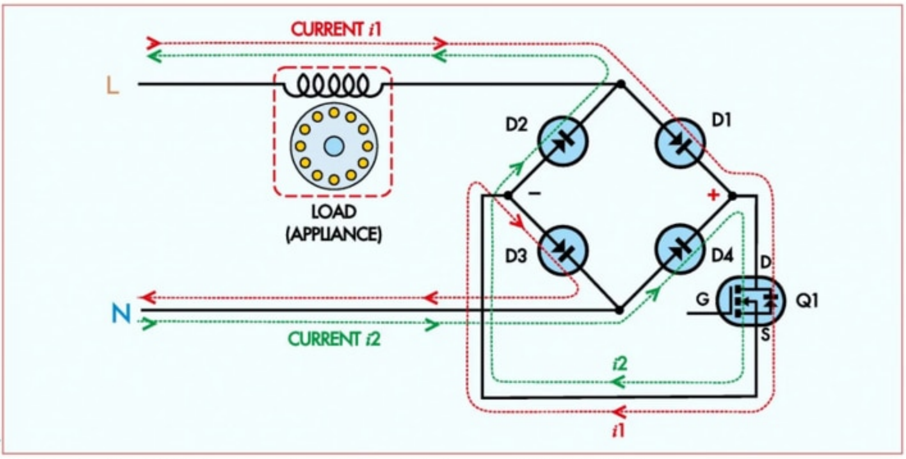


Fig.3: in the Soft Starter circuit, the N-channel MOSFET is connected to a diode bridge, so current always flows from its drain to its source. That way, its parasitic body diode is never forward-biased. The current paths are shown for when the live conductor is more positive than the neutral (i1) and for when the live is negative with respect to neutral (i2).

Warning: Mains Voltage

The entire circuit of the Active Soft Starter floats at mains potential and could be lethal should you make contact with it. Don't assume that because we use isolation between different parts of the circuit that some parts are safe to touch – they are not! The isolation between parts of the circuit is to allow for the differing voltage potentials in parts of the circuit rather than for safety.

'trailing-edge phase control' and differs from the 'leading-edge phase control' method that is often used.

Leading edge vs trailing edge

Fig.1 shows the mains waveform, while Fig.2 shows these two types of power control. Our mains electricity supply (nominally 230V AC) is a sinewave that repeats 50 times per second (ie, at 50Hz). For phase control, power is applied over a portion of each half of the mains cycle.

The waveforms labelled 'A' in Fig.2 show the situation when there is a small phase angle of the full sinewave applied to the load. In the left-hand waveform, the voltage is applied to the load from late in the waveform until the zero-crossing. However, on the right, the voltage is applied for a short period beginning from 0V, switching off a little while later.

Both waveforms apply the same RMS voltage to the load and have the same area under the shaded portion of the sinewave curve. The difference is that one switches on at the end of the half cycle (leading-edge phase control), while the other switches on at the beginning of the cycle (trailing-edge phase control).

Leading edge phase control has been used for around 50 years, mainly for dimming incandescent lamps. That is because it can be implemented using a simple circuit based on a Triac, a semiconductor device that switches on when its gate is driven. It can't be switched off via the gate; instead, it switches itself off when the current flow through it drops to near zero.

However, leading-edge phase control is unsuitable for providing soft starting to loads that charge a capacitor. If a voltage is suddenly applied to that type of circuit, it will create a high surge current, regardless of whether the phase angle it is on for is only a small portion of the mains waveform.

The solution is to use a trailing-edge phase control instead. The switching device now turns on at the mains zero-crossing where there is little or no potential difference between live and neutral. The voltage then rises relatively slowly, following the sinewave shape, to charge the capacitance.

Current is drawn from the mains in much smaller and more tolerable pulses. Note that a typical circuit that charges capacitors includes a rectifier so that the capacitor is charged with DC voltage.

For soft starting, we increase the duration of the waveform applied to the load over time, so the capacitor charges in small increments as the next cycle has a slightly greater phase length and hence a slightly higher peak voltage. The capacitor is ultimately charged, but at a slower rate than if the full supply were applied at power on.

By the way, trailing-edge control is also used for dimming LED lamps because they are usually powered by a capacitor-input switch-mode power supply (SMPS). The disadvantage of trailing-edge phase control is that a Triac cannot be used. It needs a switching device that can be switched off at any part of the mains waveform.

Fig.3 is a simplified version of how we implement trailing-edge phase control. We use a metal-oxide semiconductor field effect transistor (MOSFET) and a rectifier bridge. The MOSFET is connected within the diode bridge, so current always flows from its drain terminal to its source.

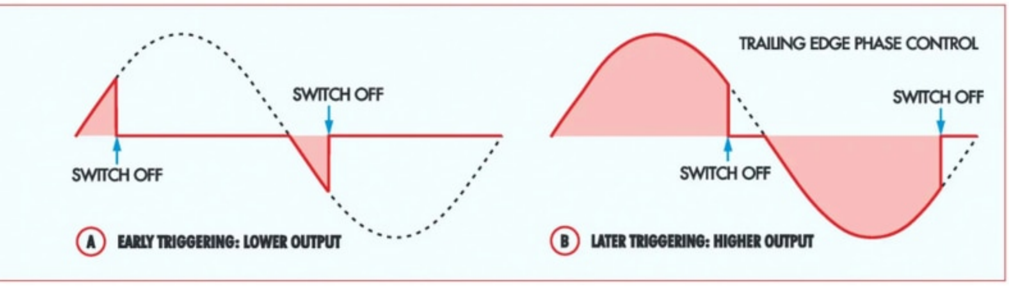
The current paths are shown for when the live is more positive than the neutral (i1) and for when the live is negative with respect to neutral (i2). The MOSFET circuit allows us to switch mains power to the load on or off at any point in the mains cycle.

Results

We measured the startup current for a bank of amplifiers that, when switched on normally, would trip the circuit breaker. We also tested it with a 750W angle grinder.

For the amplifiers, the startup load is essentially a bank of capacitors that charges up at power-on. When discharged, they effectively form a short circuit, resulting in a huge current flow as power is first applied. This is shown in Scope 1, with each vertical division corresponding to 50A (10A = 1V here).

The startup surge current (sometimes called the inrush current)


TRAILING EDGE PHASE CONTROL
SWITCH OFF
SWITCH OFF
SWITCH OFF
SWITCH OFF
A EARLY TRIGGERING: LOWER OUTPUT
B LATER TRIGGERING: HIGHER OUTPUT

Trailing-edge phase control achieves a similar result, but instead, the load is switched on at the zero crossing and then switched off at some point later in the mains cycle. The later the switch-off, the more power is applied to the load.

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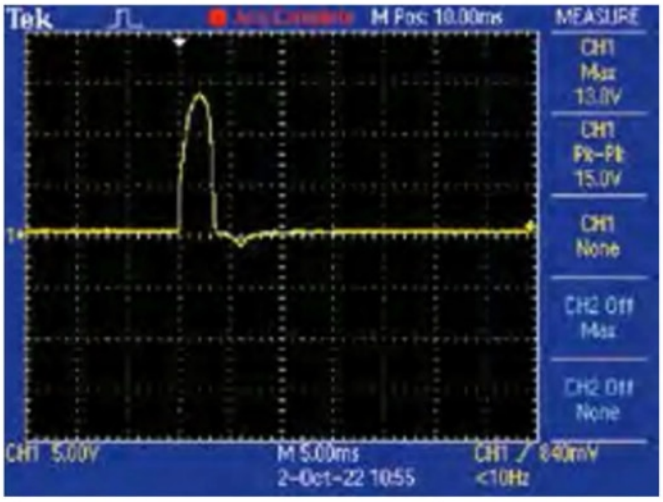
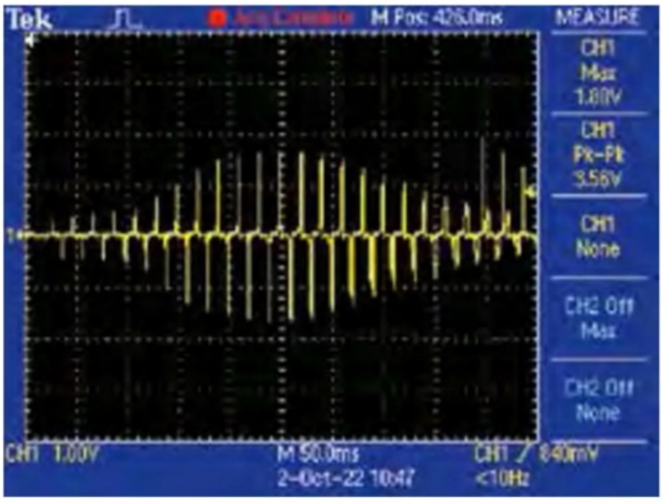
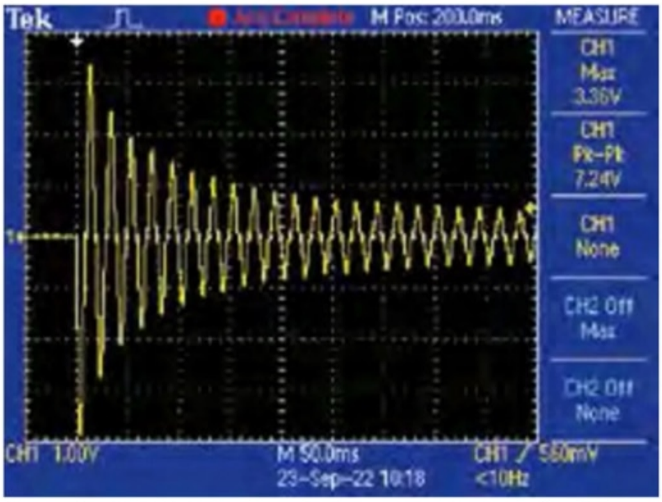

Tek
M Pos: 10.00ms
MEASURE
CH1 Max 13.8V
CH1 Pk-Pk 15.0V
CH1 None
CH2 Off Max
CH2 Off None
CH1 5.00V
M 5.00ms
2-Oct-22 10:55
CH1 / 840mV
<10Hz

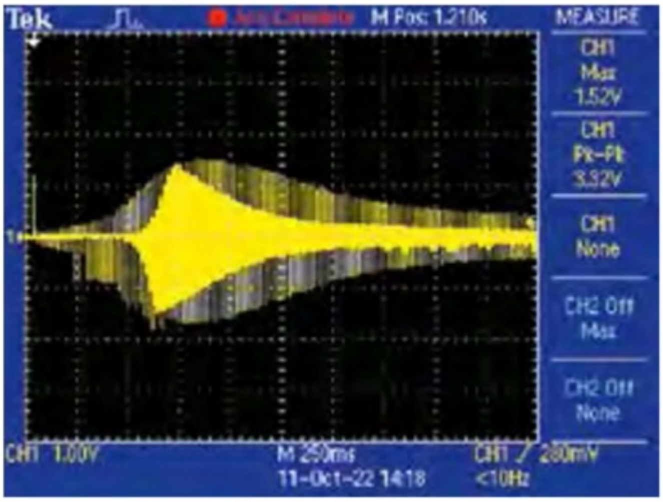
Scope 1: switching on a bank of amplifiers, the current peaks at 138A until the circuit breaker trips after 6ms.


Tek
M Pos: 426.0ms
MEASURE
CH1 Max 1.80V
CH1 Pk-Pk 3.56V
CH1 None
CH2 Off Max
CH2 Off None
CH1 1.00V
M 50.0ms
2-Oct-22 10:47
CH1 / 840mV
<10Hz

Scope 2: with the Soft Starter, the bank of amplifiers can be switched on without tripping the breaker.


Tek
M Pos: 200.0ms
MEASURE
CH1 Max 3.36V
CH1 Pk-Pk 7.24V
CH1 None
CH2 Off Max
CH2 Off None
CH1 1.00V
M 50.0ms
23-Sep-22 10:18
CH1 / 560mV
<10Hz

Scope 3: the 750W angle grinder draws 40A on the first mains cycle, dropping to 6A after half a second.


Tek
M Pos: 1.210s
MEASURE
CH1 Max 1.52V
CH1 Pk-Pk 3.32V
CH1 None
CH2 Off Max
CH2 Off None
CH1 1.00V
M 250ms
11-Oct-22 14:18
CH1 / 280mV
<10Hz

Scope 4: with the Soft Starter, the angle grinder takes four times longer to spin up and no longer kicks.

peaks at about 138A before the circuit breaker trips. The time for the circuit breaker to trip is less than a mains half-cycle of 10ms (we measure 6ms to the small negative spike).

Scope 2 shows the startup current for the same load with the *Active Soft Starter* connected, over a longer period (the timebase is now 50ms instead of 5ms). The is much more subdued, with only small peaks to a maximum of around 17A. The amplifier capacitor banks are fully charged after about 500ms, hence the drop-off in the current spikes.

For the 750W angle grinder, the startup current (Scope 3) peaks at nearly 40A in the negative direction and then about 34A in the positive direction, tapering down to about 6A after 450ms. With the *Soft Starter* connected (Scope 4, again with a longer timebase), a small initial current rises to about 13A peak after 750ms and tapers to about 5A at the two-second mark.

The fact that it takes considerably longer to spin up indicates that it has much less of a 'kick' to it.

Block diagram

Block diagram Fig.4 shows how the circuitry is arranged in the *Active Soft Starter*. Incoming mains live (L) passes through a fuse and to the mains output for connection to the appliance while current transformer T1 monitors the current flow.

The incoming neutral (N) does not directly connect to the output, but instead, goes via the soft-start circuitry comprising MOSFET Q1 and bridge rectifier BR1. The relay bypasses this arrangement after the soft-start period.

The live mains wire passes through the centre of the current transformer T1 twice, forming its primary winding. The isolated secondary winding produces a voltage proportional to the live current. This is rectified using a precision full-wave rectifier and low-pass filtered to give a smoother DC voltage, then fed to the AN1 analogue input of microcontroller IC1.

The current measurement is used for two purposes. One is to monitor when the appliance is switched on to initiate soft starting. The other is to determine when the appliance is switched off, to reset the circuitry, ready for the next power-on.

Microcontroller IC1 controls all the *Soft Starter* functions. It monitors the appliance current, controls the gate of MOSFET Q1 and the coil of the relay, monitors the soft start rate setting potentiometer and also monitors the mains waveform zero-crossing timing.

The gate drive for the MOSFET needs to be referenced to the negative terminal of the bridge rectifier, which is neither at neutral nor live potential. So For IC1 to drive the MOSFET, there needs to be electrical isolation between IC1 and Q1's gate. This is achieved using an isolated power supply and an isolated gate driver.

The isolated supply is produced via the GP4 digital output of IC1 that delivers a 1MHz, 5.5V square wave. That waveform is stepped up and isolated via transformer T2. After rectification and filtering, the result is a DC voltage suitable for driving the gate of Q1.

The MOSFET gate is controlled via the GP0 digital output of IC1. This drives an opto-coupler (IC3) containing an infrared LED that is electrically

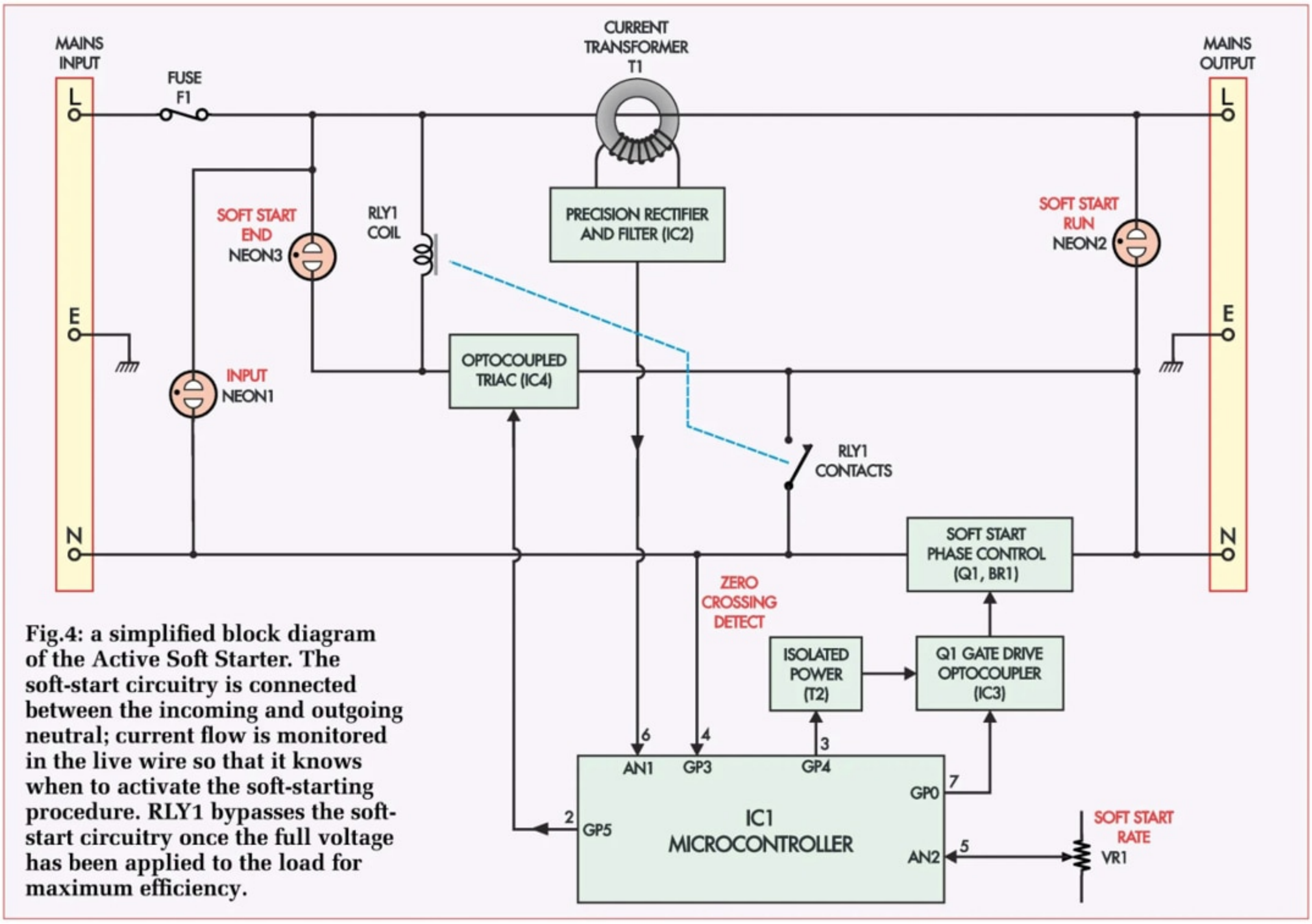


Fig.4: a simplified block diagram of the Active Soft Starter. The soft-start circuitry is connected between the incoming and outgoing neutral; current flow is monitored in the live wire so that it knows when to activate the soft-starting procedure. RLY1 bypasses the soft-start circuitry once the full voltage has been applied to the load for maximum efficiency.

isolated from the opto-coupler's optically switched transistor. That transistor controls the voltage at the gate of MOSFET Q1.

The isolated drive for the relay coil is via an optically coupled Triac driver (IC4) that connects the lower end of the coil to the output neutral. The relay has a 230V AC coil with the top end connected to live and the bottom end to IC4.

IC4 has an internal LED that optically triggers the output Triac. It is typically used to drive the gate of a larger Triac, but for our circuit, we are just using it to power the relay coil.

The power supply for IC1 is not shown in Fig.4; its supply is derived via a mains-rated capacitor that acts as a current limiter to a zener diode clamp, resulting in the 5.5V supply voltage. The positive side of this supply is referenced to mains live.

Potentiometer VR1 is used for the soft start rate adjustment. It is connected across that 5.5V supply, producing a varying voltage at the microcontroller's AN2 analogue input.

Neon indicators

NEON1 lights when there is mains power at the input. NEON2 is connected across the mains output, so it starts dim and reaches full brightness when the soft start period ends. We call this the 'run' indicator. Finally, NEON3 lights when the relay is on after the soft start period completes. This is called the soft start 'end' indicator.

Circuit details

The entire circuit is shown in Fig.5. A lot of the circuitry has already been explained by the block diagram. However, several parts of the circuit haven't been described in any detail.

As mentioned earlier, Triac-output opto-coupler IC4 drives the relay coil. We are using the MOC3042 with zero voltage-crossing detection, so its Triac always switches on when the mains supply is at zero voltage. That is not strictly necessary for our circuit, but it does not hurt. Its internal Triac between pins 4 and 6 is guaranteed to trigger, provided there is at least 10mA through the internal infrared LED between pins 1 and 2.

We also include a snubber across the Triac terminals, comprising a 22nF X2-rated mains capacitor and a 150Ω resistor, connected in series between its pins 4 and 6. This limits the voltage rise time so that the Triac will not switch itself on when power is first applied to the circuit.

The 1MΩ resistor just discharges the capacitor when power is off for safety.

The snubber limits sudden voltage rises across the Triac by charging over time via the 150Ω resistor. This prevents the voltage from rising faster than 1000V/µs, which is the maximum dV/dt rating for the Triac in IC4, below which it is guaranteed not to switch on by itself.

Another precaution against that is connecting pin 4 of the Triac to the neutral output of the soft-start circuitry rather than directly to the incoming neutral. So when power is first applied, there is no voltage across the Triac. As the soft start process begins, the voltage across it rises at a controlled rate.

Protecting MOSFET Q1

As well as a snubber for IC4, there is a 220nF/470Ω snubber across the AC terminals of BR1 to reduce the magnitude of voltage spikes seen by MOSFET Q1. This also has a 1MΩ bleeder resistor for safety. This snubber also provides a small current flow when an appliance is switched on before the soft starting process has activated. This is enough current to detect and initiate the soft start.

Q1 is also protected against overvoltage conditions that could destroy the device; it has a 500V maximum drain-source rating. Two transient voltage suppressors (TVS) are used to prevent the voltage from going over that limit.

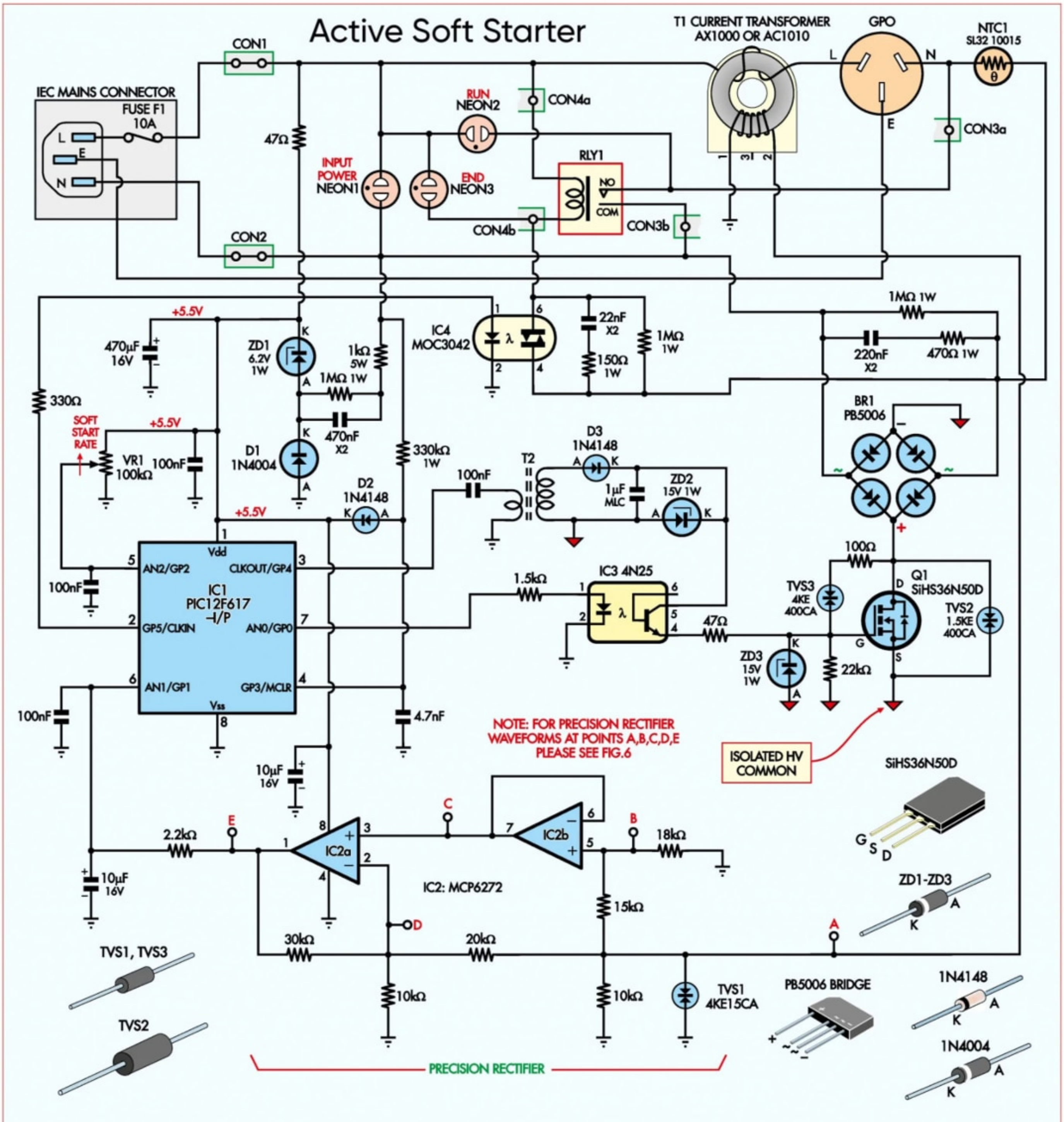

Active Soft Starter
IEC MAINS CONNECTOR
FUSE F1 10A
L
E
N
CON1
CON2
47Ω
INPUT POWER NEON1
RUN NEON2
END NEON3
CON4a
CON4b
RLY1
NO
COM
CON3b
T1 CURRENT TRANSFORMER AX1000 OR AC1010
1 3 2
GPO
L N E
CON3a
NTC1 SL32 10015
θ
+5.5V
470µF 16V
ZD1 6.2V 1W
K A
1kΩ 5W
1MΩ 1W
470nF X2
IC4 MOC3042
1 2 6 4
22nF X2
150Ω 1W
1MΩ 1W
1MΩ 1W
220nF X2
470Ω 1W
BR1 PB5006
330Ω
SOFT START RATE
VR1 100kΩ
100nF
D1 1N4004
330kΩ 1W
D2 1N4148
100nF
T2
D3 1N4148
1µF MLC
ZD2 15V 1W
IC1 PIC12F617 –I/P
Vdd
AN2/GP2
CLKOUT/GP4
GP5/CLKIN
AN0/GP0
AN1/GP1
GP3/MCLR
Vss
1.5kΩ
IC3 4N25
47Ω
100Ω
TVS3 4KE 400CA
Q1 SiHS36N50D
D G S
TVS2 1.5KE 400CA
ZD3 15V 1W
22kΩ
100nF
4.7nF
NOTE: FOR PRECISION RECTIFIER WAVEFORMS AT POINTS A,B,C,D,E PLEASE SEE FIG.6
ISOLATED HV COMMON
SiHS36N50D
G S D
10µF 16V
2.2kΩ
E
C
B
IC2a
IC2b
18kΩ
10µF 16V
IC2: MCP6272
D
15kΩ
ZD1-ZD3
A K
A
30kΩ
20kΩ
10kΩ
10kΩ
TVS1 4KE15CA
TVS1, TVS3
TVS2
PB5006 BRIDGE
+ ~ ~ –
1N4148
1N4004
PRECISION RECTIFIER

Fig.5: IC1 is the controlling PIC while generating an isolated MOSFET gate voltage supply by feeding a high-frequency square wave into transformer T2. It controls the MOSFET gate across that isolation barrier using opto-coupler IC3, and it monitors the output of the current-sense transformer via the full-wave precision rectifier formed by dual op amp IC2. Two transient voltage suppressors and a zener diode protect MOSFET Q1 from voltage spikes.

TVS2 is connected directly between the MOSFET's drain and source and conducts to shunt voltage at the TVS clamp voltage of 400V (255V AC rectified gives ~360V DC). However, this TVS can be damaged if the overvoltage spike has too much energy, so a second line of defence is used.

A second TVS, TVS3, is connected in series with a 100Ω resistor between the MOSFET drain and gate. If the drain voltage rises too high, TVS3 conducts and causes the MOSFET gate voltage to rise, so the MOSFET starts to conduct, shunting the voltage spike itself.

Zener diode ZD3 prevents the gate voltage from going over 15V in this case, which could otherwise damage it, while the 100Ω resistor limits the zener current to a safe level.

Current detection

Current transformer T1 produces an output current from its secondary winding that's proportional to the current flow through the live mains wire. The 10kΩ loading resistor gives about 4V AC output with a current flow of 1A and one turn of the live mains wire through the current transformer core. We use two turns through the core, giving about 4V AC with 500mA current through the primary.

While the input-current-to-output-voltage conversion is not very linear using a 10kΩ loading resistance, we use the high value to improve sensitivity. A 100Ω loading resistor would be used instead for this current transformer to measure current accurately. That would provide a more linear relationship but only gives 1V AC for a 10A primary current.

Current sense voltage rectification

Another transient voltage suppressor (TVS1) clamps the output voltage from transformer T1. This limits the current into the following op amp inputs to a safe level.

The output from T1 needs to be rectified to give a DC voltage suitable for monitoring by microcontroller IC1. A precision full-wave rectifier is used, made from dual op amp IC2 and associated resistors; note the lack of diodes.

The gain of this precision rectifier is 1.5 times. While it may appear impossible to rectify the incoming AC voltage without diodes, it is possible, provided that the op amp has specific characteristics.

The op amp needs to be able to operate with an input *below* its negative supply rail, and the op amp must be able to pull its output close to that negative supply rail.

Here, we are using an MCP6272 dual op amp (IC2). One stage (IC2b) is connected as a unity-gain buffer, while the other (IC2a) provides the 1.5-times gain.

To understand how the rectification works, refer to Fig.6, where A to E correspond to the waveforms at the identically labelled parts of the circuit in Fig.5. That is assuming that our example waveform is present at point A.

Sample waveform A is a 2V peak-to-peak sinewave. For the negative half of the cycle, the signal applied to the non-inverting pin 5 input of IC2b via the 15kΩ resistor will cause the voltage at that pin (point B) to be clamped at around –0.3V due to IC2's internal input protection diode.

The output of IC2b (point C) therefore sits at 0V during negative portions of the cycle, since its negative supply rail is at 0V, and it cannot pull its output lower than that.

IC2a adjusts its output (point E) so that the voltage at its inverting input pin 2 (point D) matches the voltage at non-inverting input pin 3 (point C). Since the 10kΩ resistor from point D to ground has no voltage across it, it plays no part in the circuit during the negative portions of the cycle.

With the 10kΩ resistor essentially out of the circuit, IC2a operates as a standard inverting amplifier with both inputs (points C and D) at 0V. Its gain is therefore –30kΩ divided by 20kΩ, which equals –1.5 times. So the –1V peak of the waveform is amplified and inverted to produce +1.5V at point E.

The way it works for a positive voltage at the input (point A) is more complicated. First, the voltage at pin 5 (point B) is reduced compared to the 1V peak at the input. This is because of the divider formed by the 15kΩ and 18kΩ resistors, so the voltage becomes 0.5454V (ie, 1V × 15kΩ /[15kΩ + 18kΩ]).

Point C will also peak at 0.5454V since IC2b is working as a unity-gain buffer producing the same voltage at its output as its non-inverting input. Once again, op amp IC2a adjusts the output voltage (point E) so that the voltage at the inverting input at pin 2 (point D) matches the voltage at the non-inverting input, pin 3 (point C).

To determine the resulting voltage, we must calculate the currents through the three resistors connecting to the inverting input of IC2a at point D.

1. The current through the 10kΩ resistor is the waveform D voltage divided by 10kΩ. This peaks at 54.54μA (0.5454V / 10kΩ).
2. For the current through the 20kΩ resistor, with 1V peak at the input (point A), there will be 22.73μA ($[1V_{[A]} - 0.54V_{[D]}] / 20k\Omega$).

So we have 22.73μA flowing into the node at point D via the 20kΩ resistor and 54.54μA flowing away from that node via the 10kΩ resistor. The extra current to balance currents at node D needs to come via the 30kΩ resistor. This is 31.81μA (54.54μA – 22.73μA). Remembering that voltage at point D peaks at 0.54V, the required voltage at point E is 1.5V (31.81μA × 30kΩ + 0.54V).

So the circuit operates as a full-wave rectifier with a gain of 1.5. The degree of precision depends on the op amp parameters and resistor tolerances. The lower the offset voltage of the op amp and the lower the op amp input bias current, the more accurate the full-wave rectification will be, particularly at low signal levels.

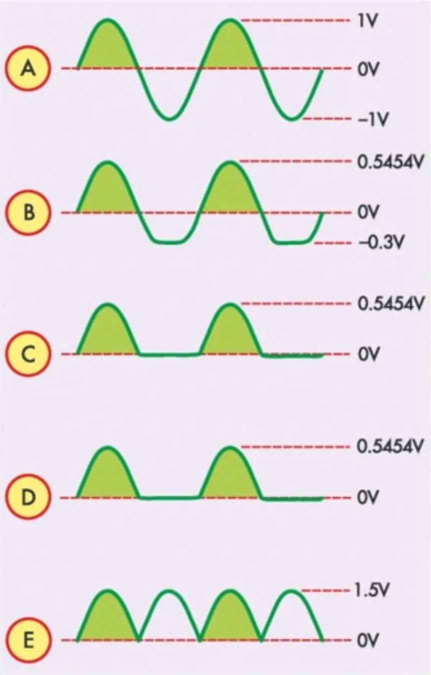
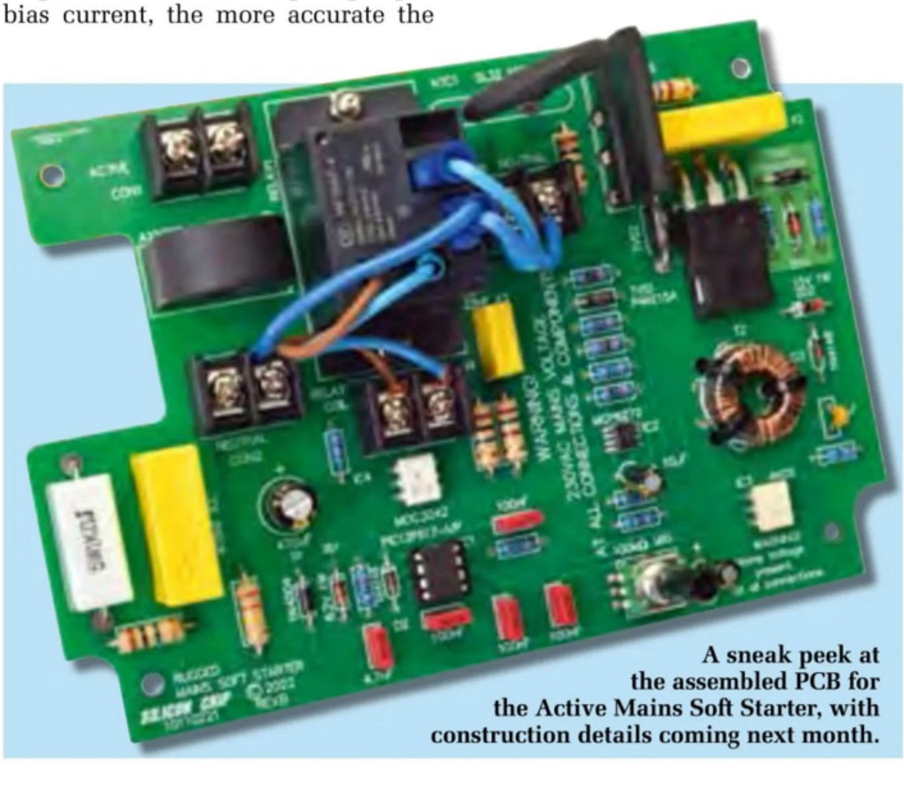


Fig.6: these waveforms demonstrate how the active precision rectifier used for current monitoring works. They correspond to the expected waveforms at the points marked A-E on the circuit for the condition where there is a 2V peak-to-peak sinewave at point A, corresponding to a resistive load drawing about 88mA RMS.

Fortunately, we are not overly concerned with absolute accuracy here. We just need full-wave rectification of the incoming AC signal from the current transformer.

Scope 5 shows the 1V peak sinewave at the input to the full-wave



A sneak peek at the assembled PCB for the Active Mains Soft Starter, with construction details coming next month.

rectifier (point A) on channel 1, shown in yellow. Below that is the full-wave rectified waveform at point E, shown in cyan.

A 2.2kΩ resistor and 10μF capacitor filter the rectified waveform to produce a smoothed DC voltage suitable for the IC1 to monitor via its AN1 analogue input and internal analogue-to-digital converter (ADC).

Mains zero-crossing detection

IC1 monitors the mains waveform at the mains neutral via a 330kΩ 1W resistor. The voltage at its pin 4 digital input (GP3) is filtered with a 4.7nF capacitor, providing a near-zero voltage when the mains voltage is at zero. IC1's pin 4 input detects when this voltage changes from being positive to zero or negative and vice versa.

The voltage at pin 4 is clamped by the internal protection diode to −0.3V during the negative part of the cycle.

For positive excursions of the mains waveform, diode D2 clamps the voltage to about 0.6V above the 5.5V supply, or close to 6V. This diode is required since the pin 4 input is not protected with a diode to the positive supply. That's so this input can be used for programming the microcontroller, where the voltage at this pin needs to go above the supply voltage.

MOSFET gate drive

To drive the MOSFET gate, we need an isolated DC supply and a method of connecting and disconnecting that supply to the gate. As mentioned previously, these voltages need to be galvanically isolated from IC1.

The isolated DC supply is generated by applying a 1MHz square wave to the primary winding of high-frequency transformer T2 from IC1's clock output at GP4 (pin 3). This is pne quarter of the frequency of its internal 4MHz oscillator. The primary has 10 turns, while the secondary has 48, giving a 4.8:1 voltage ratio.

Since the primary is a 5.5V peak-to-peak square wave, we can expect the secondary to deliver a 26.4V (5.5V × 4.8) peak-to-peak square wave. After half-wave rectification by diode D3, we obtain a 13.2V DC output that is filtered by a 1μF capacitor. 15V zener diode ZD2 limits the voltage to a safe level for the MOSFET gate.

The Opto-coupled output transistor of IC3 switches the MOSFET gate on or off. It is driven by the pin 7 digital output (GP0) of IC1. When this is high (at 5.5V), it drives the internal infrared LED of IC3 via a 1.5kΩ current-limiting resistor. The LED then lights and switches on the output transistor within IC3 that connects the 13.2V DC supply to the gate of Q1 via a 47Ω resistor.

When the GP0 output of IC1 goes low (to 0V), IC3's LED switches off, so the gate of Q1 is pulled to 0V by the 22kΩ resistor, switching the MOSFET off.

Parts List – Active Soft Starter

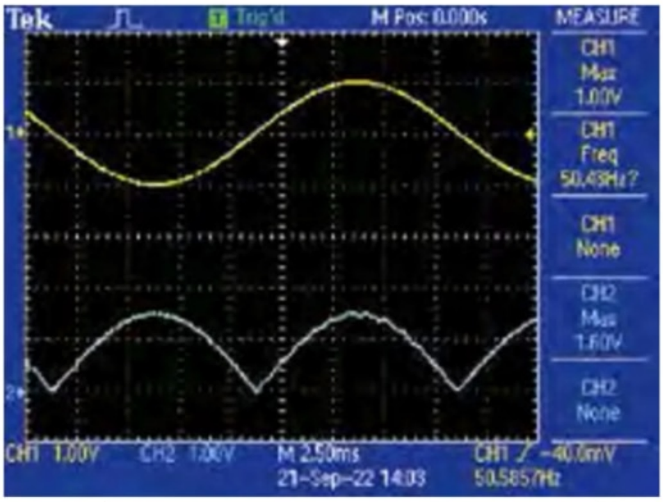
1 double-sided, plated-through PCB coded 10110221, 159 × 109mm availabe from the *PE PCB Service*
1 171 × 121 × 55mm polycarbonate or ABS enclosure **[Altronics H0478, Jaycar HB6218]**
1 153 × 107mm panel label
1 10A IEC panel-mount mains input socket with integral fuse holder **[Altronics P8324, Jaycar PP4004]**
1 10A IEC mains power lead
1 mains GPO socket **[Altronics P8241, Jaycar PS4094] (UK builders source UK socket)**
1 Talema AX1000 or AC1010 10A current transformer (T1)
1 Hongfa HF105F-4/240A1HSTF 30A 240VAC chassis mount relay, 240V AC coil (RLY1)
1 SL32 10015 15A 265V AC NTC thermistor (NTC1)
3 plastic-bodied mains neon indicators (NEON1-NEON3; **optional**) **[Altronics S4016, Jaycar SL2630]**
1 10A M205 fast-blow fuse (F1)
4 2-way 15A 300V screw barrier terminals (CON1-CON4) **[Altronics P2101]**
1 100kΩ linear PCB-mount potentiometer (VR1) **[Altronics R1948]**
1 8-pin DIL IC socket (for IC1)
1 18 × 10 × 6mm ferrite toroid (for T2) **[Jaycar LO1230]**

Hardware and wire
1 1.25m length of 0.25mm diameter enamelled copper winding wire (for T2)
2 4.8mm insulated female spade crimp lugs
1 350mm length of **(blue and brown)** 7.5A mains-rated wire
1 200mm length of blue 10A mains-rated wire
1 250mm length of brown 10A mains-rated wire
1 150mm length of green/yellow striped 10A mains-rated wire
1 75mm length of 10mm diameter heatshrink tubing
1 20mm length of 5mm diameter **(blue, red and green)** heatshrink tubing ★
1 20mm length of 3mm diameter **(blue and red)** heatshrink tubing ★
1 20 × 15mm piece of thermal transfer tape **[Altronics H7240, Jaycar NM2790]**
2 M3 × 10mm Nylon countersunk machine screws
2 M3 × 15mm panhead machine screws
4 M3 × 6mm panhead machine screws
4 M3 hex nuts
17 100mm cable ties
★ *black tubing can be used instead, if preferred.*

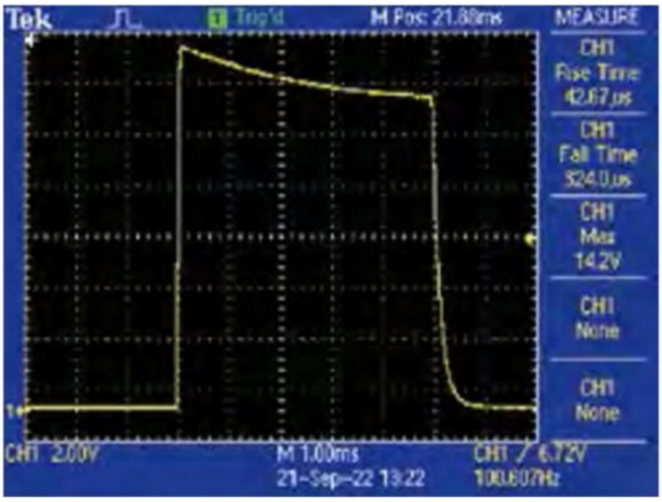
Semiconductors
1 PIC12F617-I/P 8-bit microcontroller programmed with 1011022A.hex, DIP-8 (IC1)
1 MCP6272T-E/SN dual rail-to-rail op amp, SOIC-8 (IC2)
1 4N28 or 4N25 opto-coupler, DIP-6 (IC3)
1 MOC3042M or MOC3043M zero-crossing triggered Triac driver, DIP-6 (IC4)
1 SIHS36N50D-GE3 36A 500V N-channel MOSFET, TO-247 (Q1)
1 PB5006 45A 600V bridge rectifier (BR1)
1 6.2V 1W zener diode (ZD1) **[1N4735]**
2 15V 1W zener diodes (ZD2, ZD3) **[1N4742]**
1 4KE15CA bidirectional TVS, 400W, 12.8V standoff (TVS1) **[Jaycar ZR1160]**
1 1.5KE400CA bidirectional TVS, 1500W, 342V standoff (TVS2) **[Jaycar ZR1180]**
1 4KE400CA bidirectional TVS, 400W, 342V standoff (TVS3) **[Jaycar ZR1164]**
1 1N4004 400V 1A diode (D1)
2 1N4148 75V 200mA diodes (D2, D3)

Capacitors
1 470μF 16V PC electrolytic
2 10μF 16V PC electrolytic
1 1μF 50V multi-layer ceramic
1 470nF X2-rated metallised PP
1 220nF X2-rated metallised polypropylene (PP)
4 100nF 63V or 100V MKT polyester
1 22nF X2-rated metallised polypropylene (PP)
1 4.7nF 63V or 100V MKT polyester

Resistors *(all ½W metal film ±1% unless noted)*
3 1MΩ 1W ±5%
1 330kΩ 1W ±5%
1 30kΩ
1 22kΩ
1 20kΩ
1 18kΩ
1 15kΩ
2 10kΩ
1 2.2kΩ
1 1.5kΩ
1 1kΩ 5W ±5% wirewound
1 470Ω 1W ±5%
1 330Ω
1 150Ω 1W ±5%
1 100Ω
2 47Ω



Scope 5: the input to the active rectifier at point A and the output below (point E). Note the gain.



Scope 6: the isolated MOSFET gate drive signal. It switches on faster than it switches off due to the isolation scheme.

Scope 6 shows the gate drive to the MOSFET when driven for 5ms on and 5ms off at 100Hz. When switched on, the gate voltage is initially 14.3V, drooping to 12.3V over the 5ms period. The voltage droop is due to the 1µF capacitor being loaded by the 22kΩ gate-source resistor.

The switch-on rise time is around 43µs and the fall time is 324µs. The fall time is longer due to the 22kΩ discharge resistor having a higher resistance than the opto-coupler output transistor and 47Ω resistor that charges the gate up.

Power supply

Power for microcontroller IC1 and op amp IC2 is derived directly from the mains using a 470nF X2 mains-rated safety capacitor. The circuit operates by transferring charge to a 470µF capacitor via zener diode ZD1 and diode D1.

For one polarity of the mains waveform, D1 is reverse-biased and ZD1 is forward-biased, so the charge from the 470nF capacitor is transferred to the 470µF supply filter capacitor. For the other half of the mains waveform, diode D1 is forward-biased and the zener diode clamps to 6.2V between the +5.5V supply rail and D1's cathode.

Since the forward voltage of diode D1 is about 0.7V, the overall voltage across the 470µF capacitor is limited to 5.5V (6.2V – 0.7V).

Next month

The follow-up article next month will have all the construction details for the *Active Mains Soft Starter*, along with the testing procedure and instructions for use.

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This CD-ROM version of the exciting and popular *Teach-In 8* series has been designed for electronics enthusiasts who want to get to grips with the inexpensive, immensely popular Arduino microcontroller, as well as coding enthusiasts who want to explore hardware and interfacing. *Teach-In 8* provides a one-stop source of ideas and practical information.

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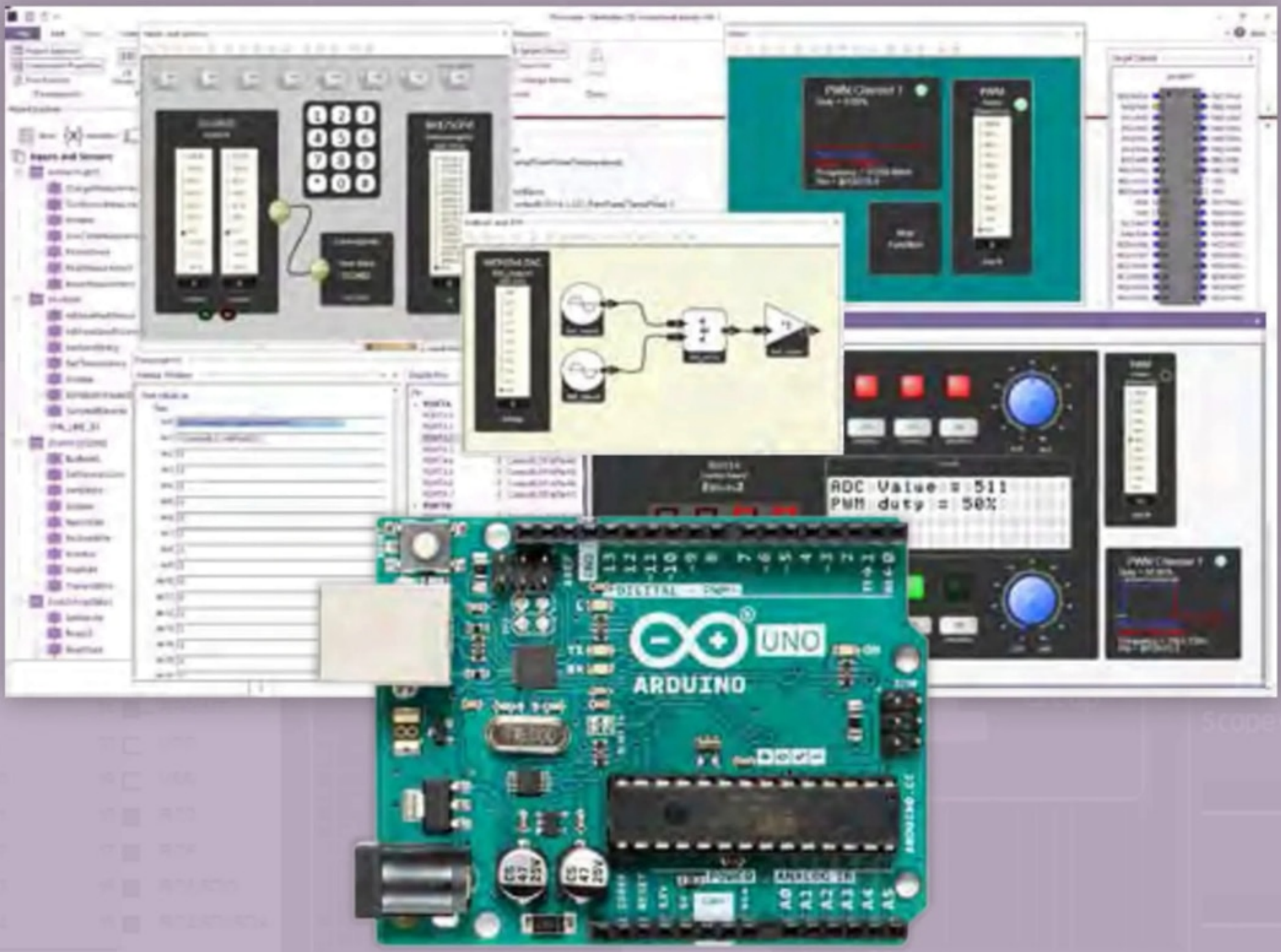
ADC Value = 511
PWM duty = 50%
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Mike & Richard Tooley

The three sections of the *Teach-In 3* CD-ROM cover a huge range of subjects that will interest everyone involved in electronics – from newcomers to the hobby and students to experienced constructors and professionals.

The first section (80 pages) is dedicated to *Circuit Surgery*, *EPE/PE's* regular clinic dealing with readers' queries on circuit design problems – from voltage regulation to using SPICE circuit simulation software.

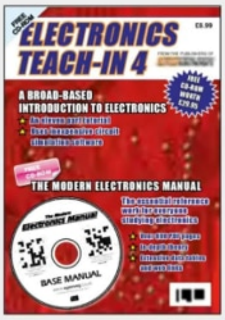
The second section – *Practically Speaking* – covers hands-on aspects of electronics construction. Again, a whole range of subjects, from soldering to avoiding problems with static electricity and identifying components is covered. Finally, our collection of *Ingenuity Unlimited* circuits provides over 40 circuit designs submitted by readers.

The CD-ROM also contains the complete *Electronics Teach-In 1* book, which provides a broad-based introduction to electronics in PDF form, plus interactive quizzes to test your knowledge and TINA circuit simulation software (a limited version – plus a specially written TINA Tutorial).

The *Teach-In 1* series covers everything from electric current through to microprocessors and microcontrollers, and each part includes demonstration circuits to build on breadboards or to simulate on your PC.

ELECTRONICS TEACH-IN 4 – CD-ROM
A BROAD-BASED INTRODUCTION TO ELECTRONICS

Mike & Richard Tooley



The *Teach-In 4* CD-ROM covers three of the most important electronics units that are currently studied in many schools and colleges. These include, Edexcel BTEC level 2 awards and the electronics units of the Diploma in Engineering, Level 2.

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JUMP START

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15 design and build circuit projects for newcomers or those following courses in school and colleges.

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A COMPREHENSIVE GUIDE TO RASPBERRY Pi

Mike & Richard Tooley

Teach-In 6 contains an exciting series of articles that provides a complete introduction to the Raspberry Pi, the low cost computer that has taken the education and computing world by storm.

This latest book in our *Teach-In* series will appeal to electronics enthusiasts and computer buffs who want to get to grips with the Raspberry Pi.

Teach-In 6 is for anyone searching for ideas to use their Pi, or who has an idea for a project but doesn't know how to turn it into reality. This book will prove invaluable for anyone fascinated by the revolutionary Pi. It covers:

- Pi programming
- Pi hardware
- Pi communications
- Pi Projects
- Pi Class
- Python Quickstart
- Pi World
- ...and much more!

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ELECTRONICS TEACH-IN 7 – CD-ROM
DISCRETE LINEAR CIRCUIT DESIGN

Mike & Richard Tooley

Teach-In 7 is a complete introduction to the design of analogue electronic circuits. It is ideal for everyone interested in electronics as a hobby and for those studying technology at schools and colleges. The CD-ROM also contains all the circuit software for the course, plus demo CAD software for use with the *Teach-In* series.

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The Arduino offers a truly effective platform for developing a huge variety of projects; from operating a set of Christmas tree lights to remotely controlling a robotic vehicle through wireless or the Internet.

Teach-In 8 is based around a series of practical projects with plenty of information for customisation.

This book also includes *PIC n' Mix*: 'PICs and the PICkit 3 – A Beginners guide' by Mike O'Keefe and *Circuit Surgery* by Ian Bell – 'State Machines part 1 and 2'.

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- PICkit 3 User Guide
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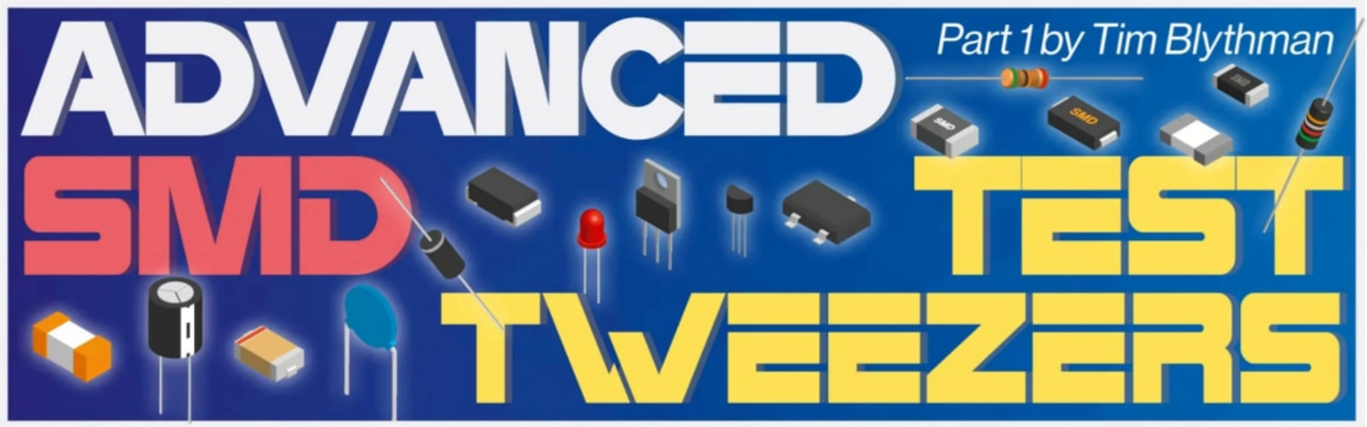
ADVANCED SMD TEST TWEEZERS

Part 1 by Tim Blythman



The SMD Test Tweezers and their successor, the Improved SMD Test Tweezers, are both simple but useful tools. We have developed an enhanced version with many more features and other improvements, such as a larger screen and an easier-to-use interface.

If you have not already built an *SMD Tweezers* kit, you may be wondering what the fuss is about.

After publishing our simple design from October 2022 and the subsequent refresh in May 2023, we were left with no doubt that both variants were very popular, with many kits sold.

Both these designs used a tiny 8-pin 8-bit microcontroller run from a single CR2032 coin cell to probe components by applying voltage via a resistor. The original *Tweezers* measured resistance, capacitance or diode forward voltage and displayed the readings on a tiny OLED screen.

The *Improved Tweezers* used the same hardware but a microcontroller with more Flash memory, allowing us to add extra features, such as the ability to flip the display to suit being used in either hand and an expanded capacitance range.

Advancements

Both those variants of the *Tweezers* were designed with small size, low cost and simplicity in mind. They both used just about the cheapest microcontroller and smallest display possible. Given their popularity, we had to produce a follow-up, and knew it needed to be good.

To be clear, this is not an incremental change over the first two designs, but a vast improvement. You can see from the list of features that the *Advanced Tweezers* will do much more than its predecessors.

One of the things we looked for in a new microcontroller for the *Advanced Tweezers* was a 12-bit ADC (analogue-to-digital converter) peripheral. This would provide extra resolution over the 10-bit ADC that is standard on most 8-bit PIC microcontrollers, such as those we used for the previous *Tweezers*.

We reviewed some of the newer 8-pin PICs in October 2023, and have since started using the PIC16F18146 in some projects. However, we chose not to use an 8-bit PIC for our *Advanced Tweezers*.

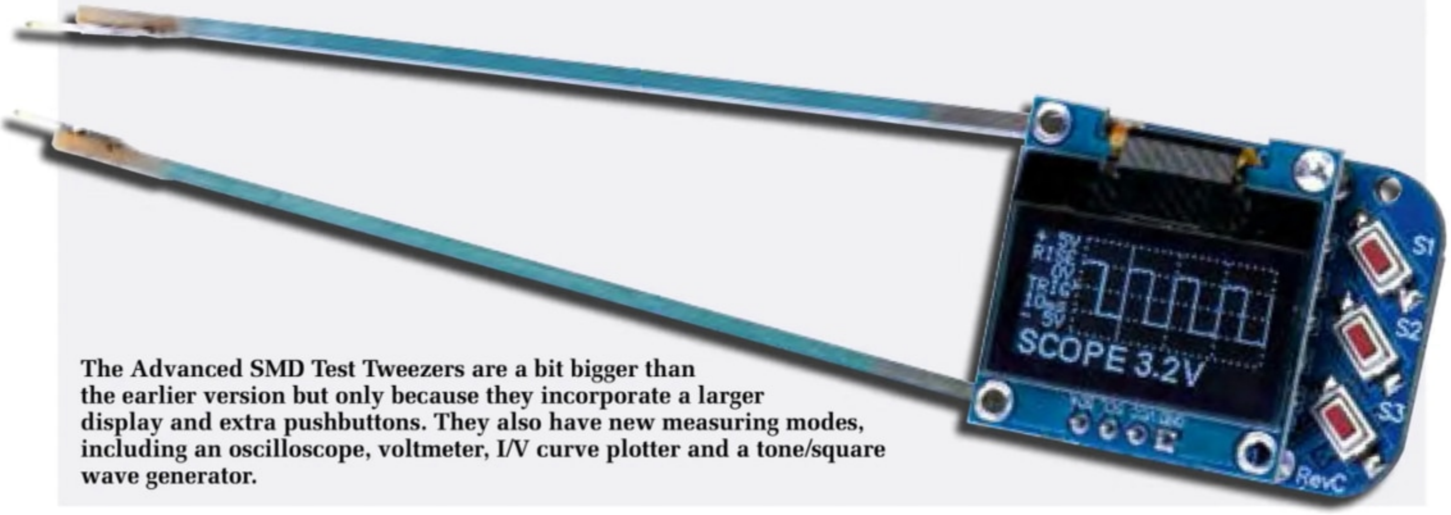
Instead, we have chosen a 28-pin 16-bit micro, the PIC24FJ256GA702. It also has a 12-bit ADC peripheral, so we still get the improved resolution. It also has some other interesting peripherals that we've put to good use.

It isn't much more expensive than an 8-bit micro, but it is undoubtedly a lot more capable. Importantly, it has much more RAM and Flash memory, so we can include many more modes and settings. That extra memory also means that the blocky font used on the earlier *Tweezers* versions has been replaced by one that is larger and much more readable.

We've also used some interesting techniques for probing and sensing. So let's introduce the various test modes that are available.

Modes

The earlier *Tweezers* variants only had a single mode which would try to identify the device under test and display its value. For a resistor



The Advanced SMD Test Tweezers are a bit bigger than the earlier version but only because they incorporate a larger display and extra pushbuttons. They also have new measuring modes, including an oscilloscope, voltmeter, I/V curve plotter and a tone/square wave generator.

or capacitor, it would show resistance or capacitance. For a diode, it would work out the forward voltage and polarity and display both. Dual anti-parallel diodes, such as bi-colour LEDs, would not be detected as they conduct in both directions.

The *Advanced Tweezers* add many more modes, which we will briefly introduce before going into more detail during the usage section of the article (in the second part).

Like the older variants, several modes are for characterising components such as resistors, capacitors and diodes. Instead of attempting to identify a device under test, the *Advanced Tweezers* reports all of its assessments together. This is made possible by using a larger OLED display and removes the possibility of the *Tweezers* identifying a component incorrectly.

There are still dedicated modes for resistors, capacitors and diodes, which each display only one value in a large, clear font, but you do need to select them. These modes are especially handy when dealing with surface-mounting capacitors, which typically don't have any distinguishing markings.

The diode mode also provides a low, steady bias current which is only interrupted by the reading cycle. This has the advantage that you know immediately that the LED is working and what colour it is when it lights.

Checking the value of hard-to-read surface-mounting parts is one of the great advantages of the *Tweezers* format. It is especially handy for capacitors and LEDs, which often have subtle polarity markings.

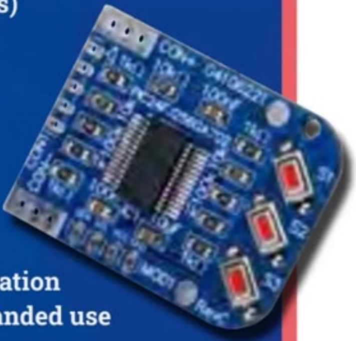
There is now also a digital voltmeter mode, which shows the voltage across the probe tips, up to ±30V.

In oscilloscope mode, it can sample at up to 25kSa/s with varying voltage and time scales. It also offers some basic trigger modes. It's not likely to make your bench 'scope obsolete, but it could be handy for probing signals in the audio range. The 'scope mode uses the same ±30V-capable input stage as the voltmeter mode, so it offers the same range.

Many current digital oscilloscopes we offer a serial decoding utility, and the *Advanced Tweezers* do too. There is only one input channel, so we can only decode a UART data stream. The *Advanced Tweezers* can accept and decode a variety of baud rates and data formats.

To overcome the limitations of the diode checker only being able to handle single diodes, we have implemented an I/V curve plotting mode.

Features and Specifications



- 10 different modes (see modes and options lists)
- Runs from a single CR2032 coin cell
- Sleep current <1μA
- Resistance accuracy ~1% when calibrated
- Voltage accuracy ~2% when calibrated
- Capacitance accuracy ~5% when calibrated
- Adjustable sleep timeout
- Adjustable display brightness
- Sleep timer can be paused for continuous operation
- Display can be rotated to suit left- and right-handed use
- Cell voltage displayed in all modes
- Auto calibration of some parameters
- Works down to 2.4V cell voltage
- Standby cell life: equal to shelf life
- Operating cell life: typically several hours of use

Modes

1. Resistance: 1Ω to 40MΩ, ±1%
2. Capacitance: 10pF to 150μF, ±5%; gives readings up to 2000μF
3. Diode forward voltage: 0-2.4V, ±2%
4. Combined resistance/capacitance/diode display
5. Voltmeter: 0 to ±30V ±2%
6. Oscilloscope: ranges ±30V at up to 25kSa/s
7. Serial UART decoder
8. I/V curve plotter
9. Logic probe
10. Audio tone/square wave generator

Oscilloscope options

- Voltage ranges: 0-5V, 0-10V, 0-20V, 0-30V, -5 to +5V, -10 to +10V, -20 to +20V, -30 to +30V
- Trigger on rising edge, falling edge, both or continuously (auto)
- Trigger level settable in 1V intervals
- Timebase (per div, 4 divs visible): 1ms, 2ms, 5ms, 10ms, 20ms, 50ms, 100ms, 200ms or 500ms

Serial UART decoder options

- Baud rate: 110, 1200, 2400, 4800, 9600, 14.4k, 28.8k, 38.4k, 57.6k or 115.2k
- 8N, 8O, 8E and 9N data length/parity
- 1 or 2 stop bits
- active high or active low
- text (terminal) or HEX display

I/V curve plotter options

- six-point sampling, live update, centred on 0V/0mA
- vertical scale (per div, four on screen): 1mA, 500μA, 200μA, 100μA or 50μA
- horizontal scale (per div, four on screen): 2V, 1V, 500mV, 200mV or 100mV

Tone/square wave generator options

- frequency: 50Hz, 60Hz, 100Hz, 440Hz or 1kHz
- nominal amplitudes (pk-pk): 300mV, 600mV, 3V or 6V
- on/off control (defaults to off)

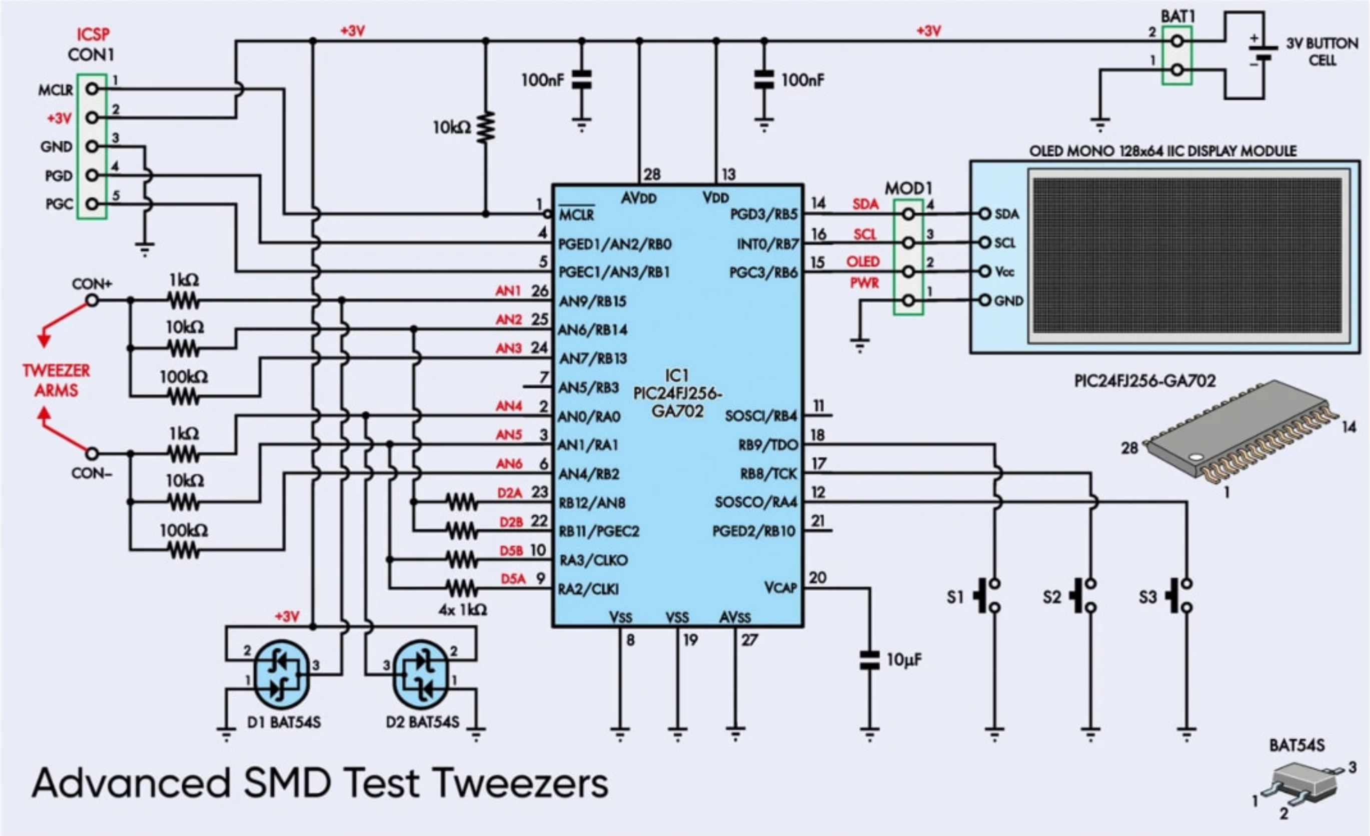

ICSP
CON1
MCLR
+3V
GND
PGD
PGC
1
2
3
4
5
+3V
100nF
10kΩ
100nF
+3V
BAT1
2
1
3V BUTTON CELL
OLED MONO 128x64 IIC DISPLAY MODULE
MOD1
SDA
SCL
OLED
PWR
SDA
SCL
Vcc
GND
28
13
AVDD
VDD
MCLR
PGED1/AN2/RB0
PGEC1/AN3/RB1
AN9/RB15
AN6/RB14
AN7/RB13
AN5/RB3
AN0/RA0
AN1/RA1
AN4/RB2
RB12/AN8
RB11/PGEC2
RA3/CLKO
RA2/CLKI
PGD3/RB5
INT0/RB7
PGC3/RB6
SOSCI/RB4
RB9/TDO
RB8/TCK
SOSCO/RA4
PGED2/RB10
VCAP
VSS
VSS
AVSS
8
19
27
IC1
PIC24FJ256-GA702
AN1
AN2
AN3
AN4
AN5
AN6
D2A
D2B
D5B
D5A
CON+
CON–
TWEEZER ARMS
1kΩ
10kΩ
100kΩ
1kΩ
10kΩ
100kΩ
4x 1kΩ
+3V
D1 BAT54S
D2 BAT54S
10μF
S1
S2
S3
PIC24FJ256-GA702
28
14
1
BAT54S
Advanced SMD Test Tweezers

Fig.1: while the 28-pin microcontroller chip is about twice the physical size of the SOIC-8 parts used for the earlier Tweezers, there are many advantages to having so many available I/O pins. 10 pins are used for probing the tips, giving much more range. Three more I/O pins handle buttons for control and calibration, while the OLED display can be powered down completely using another spare pin.

The I/V curve shape will also allow you to categorise many uknown or 'mystery' components.

The logic probe mode can differentiate between a high logic level, a low logic level and a high impedance. It also provides a digital trace so that transient signals and digital waveforms can be seen.

Finally, a Tone Generator allows square waves to be delivered at several frequencies and amplitudes. It's ideal for injecting test signals into audio equipment or a clock signal into a digital IC.

If you're working with audio gear, you might consider having two sets of *Advanced Tweezers*; one to inject a tone and a second to trace it. The *Tweezers* also have the great advantage of being battery-operated, allowing them to be used without needing to be referenced to ground.

We've provided three pushbuttons, giving more control over what the *Advanced Tweezers* are doing and making them easier to work with. This also allows us to add more extensive calibration and configuration options than the earlier variants.

Circuit details

Fig.1 shows the circuit diagram of the *Advanced Tweezers*. It has some improvements over the earlier versions that give better accuracy over a wide range of component values and also provide improved protection to the microcontroller.

IC1 is a PIC24FJ256GA702 microcontroller, and its numerous I/O pins allow us to connect to the device under test (DUT) in various ways. However, the design heritage shared with the earlier *Tweezers* is evident. Like the earlier *Tweezers*, a coin cell holder (BAT1) provides the nominal 3V supply to the circuit.

The arrangement of the arms and tips is much the same as that for the Improved Tweezers, using the same arm PCBs and gold-plated pins as simple, practical tips.

The three capacitors, and the single 10kΩ resistor connected to IC1's pin 1 are essential for any application of this microcontroller. The 10kΩ resistor pulls up the $\overline{\text{MCLR}}$ pin, allowing normal operation unless a connected programmer/debugger overrides it.

This pin and the other pins associated with programming IC1 are connected to CON1 for this purpose. You'll note that the PGED and PGEC programming pins (pins 4 and 5) are not shared with any other components, making development and debugging much easier.

The 100nF capacitors bypass the main chip supply, while the 10μF capacitor bypasses an internal regulator responsible for powering the chip's processor core.

The remaining ten resistors provide the interface between the DUT (connected to the *Tweezers* tips at CON+ and CON–) and the microcontroller.

You might note that there is no direct connection between the tips and the microcontroller; any path is always via at least one resistor. This is another improvement to the design and affords the microcontroller greater protection from the outside world. That's especially important since we envisage many

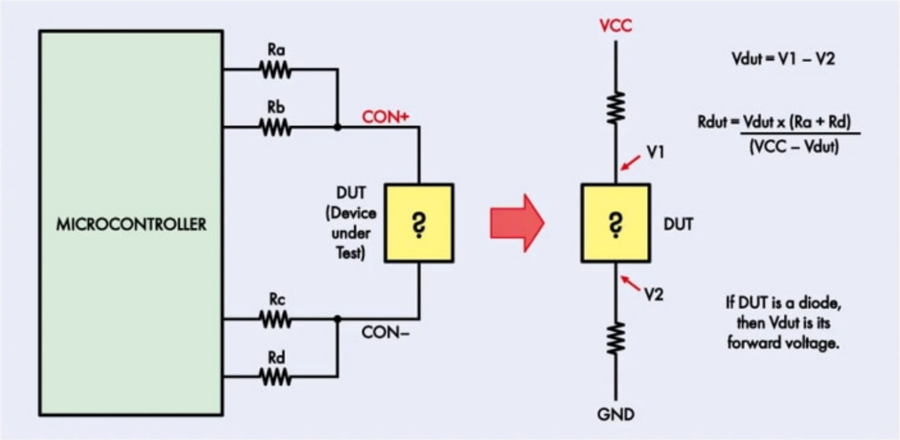

Ra
Rb
CON+
MICROCONTROLLER
DUT (Device under Test)
?
Rc
Rd
CON–
VCC
V1
?
DUT
V2
GND
Vdut = V1 – V2
Rdut = Vdut x (Ra + Rd) / (VCC – Vdut)
If DUT is a diode, then Vdut is its forward voltage.

Fig.2: the Advanced Tweezers uses IC1's internal ADC to measure voltages, using the voltage divider equation to calculate resistances and voltages across diodes. This works much the same as the earlier Tweezers, but with the addition of extra resistances and a 12-bit (instead of 10-bit) ADC to provide more range and accuracy.

users probing active circuits with the *Advanced Tweezers*.

The 1kΩ resistors to pins 2 and 26 provide the lowest-resistance path between the microcontroller and external circuitry, so we have protected each of these with a dual schottky diode clamping each to the two supply rails. These shunt excess current away from the I/O pins before any semiconductor junctions within IC1 can conduct current.

The three tactile pushbuttons, S1, S2 and S3 also connect to I/O pins on IC1. These pins are normally pulled up weakly to the positive supply internally to the microcontroller, but they go low when the button is pressed so IC1 can sense that.

MOD1 is the 0.96-inch (24mm) diagonal OLED display. It is nearly twice as wide and twice as tall as the 0.49-inch (12.5mm) OLED used in the earlier Tweezers, making for a much more legible display packed with more information.

Two I/O pins are required for its I^{2}C control interface with the microcontroller. We also use another I/O pin to power the OLED's VCC pin. That means we can completely disconnect power from the OLED module, guaranteeing it draws no current when the *Advanced Tweezers* shut down.

We had problems with some apparently faulty 0.49-inch OLEDs drawing too much current in standby mode, so we're eliminating that possibility with this new design.

Measuring resistors and diodes

Naturally, much of the *Advanced Tweezers* operation depends on the firmware. Still, before we get to that, we will explain how the microcontroller uses the sensing resistors in different ways to measure various components and voltages.

The microcontroller has an internal 1.2V bandgap voltage reference. We measure this using the ADC (with the supply as a reference) and invert the result to calculate the supply voltage. For example, if the 1.2V reference is measured as 40% of the reference voltage, the supply must be 1.2V/0.4 or 3V.

Since the internal bandgap reference can vary by up to 5% from nominal, the exact value of the reference needs to be determined during calibration for improved accuracy.

Fig.2 shows the arrangement that is used for probing resistors and diodes. Resistors R_a and R_b could be any two of the 1kΩ, 10kΩ and 100kΩ resistors available, while R_c and R_d have the same options. The micro's pins can be driven high, low or left floating (in a high-impedance mode).

R_a is typically pulled to the supply voltage by driving it high, while R_b is left high-impedance. Similarly, R_d is connected to ground by driving it low, and R_c is also high impedance. Current thus flows from the micro via R_a and into the DUT via CON+, then back to ground via CON– and R_d.

Tests are then performed with CON+ pulled low and CON– pulled high to account for reverse-biased diodes. For the following explanations, you can assume that any pins not mentioned are left in a high-impedance state, so they do not affect the calculations.

The microcontroller's ADC (analogue-to-digital converter) peripheral is used to read the voltages on the pins connected via R_b and R_c. With the ADC scaled to use the supply voltage as its reference, the actual value of the supply is not important for resistance calculations.

The calculations are made with raw ADC values. For the 12-bit ADC used on the PIC24FJ256GA702, there are 4096 steps, four times as many as with a 10-bit ADC.

The calculations make use of the voltage divider equation. Six tests are performed using various combinations of the 1kΩ, 10kΩ and 100kΩ values. These have 2kΩ, 11kΩ and 101kΩ total in series with the device under test for both polarities.

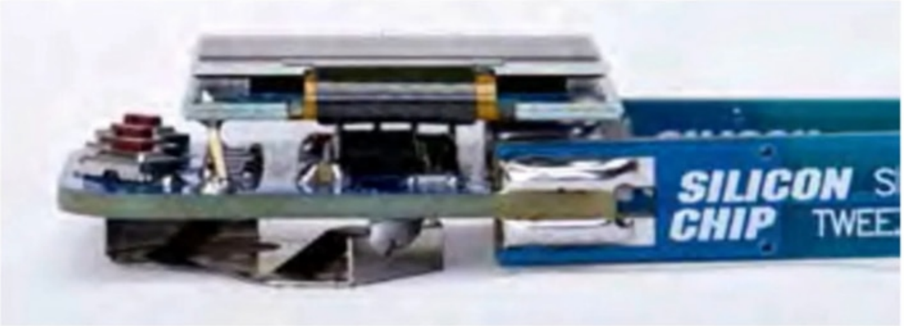
The best resolution is when the test and unknown resistors are similar in magnitude, so our algorithm discards invalid results and selects which of the measurements will give the most accurate final value.

The two tests with 2kΩ series resistance are also used for diodes. In this case, the readings are scaled by the previously calculated supply voltage to determine the diode forward voltage.

If the DUT voltage is close to the supply voltage, it is assumed that the DUT is not passing current. This will be the case for reverse-biased diodes or when no device is connected. So a diode is only detected if a voltage notably less than the supply voltage is seen in one direction and a voltage close to the supply in the other. In this case, the polarity and voltage are reported.

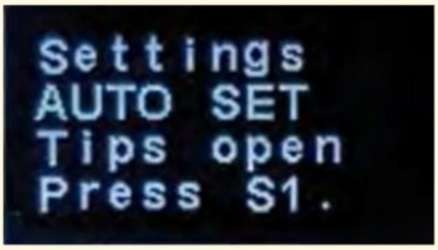
Measuring capacitors

Fig.3 shows the different arrangement used to measure the value of capacitors. One of the features of the ADC on this microcontroller is the CTMU or charge time measurement unit.



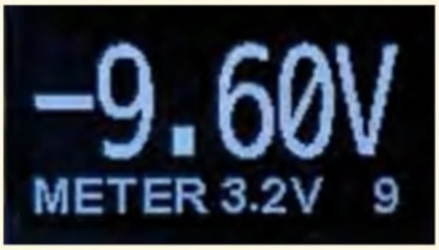
This view shows the spacing of the OLED module above the main PCB. Note the header pin acting as a reinforcing spacer at one corner of the OLED. This prevents the assembly flexing and causing a short between the two PCBs.

Screengrabs from part two, showing the Advanced SMD Test Tweezers in operation



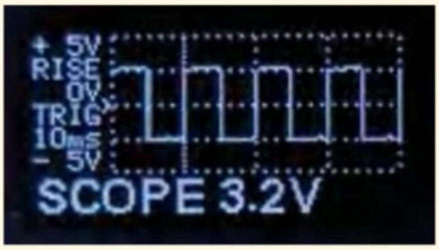
Settings
AUTO SET
Tips open
Press S1.

Screen 5: the AUTO SET tunes three calibration parameters by performing internal measurements with the tips open. It depends on the previous calibration settings being entered and correct.



-9.60V
METER 3.2V 9

Screen 14: the initial Meter display mode, which can read up to 30V with both negative and positive polarities (with respect to CON+ and CON-). The resolution is 10mV to 9.99V and 0.1V above that.



SCOPE 3.2V

Screen 15: Scope mode is handy, even though there are only 100 horizontal and 48 vertical pixels in the trace area. It samples at up to 25kHz, is suitable for audio use, and has adjustable trigger settings.

While the CTMU has many applications, what matters to us is that it includes a programmable current source that can be delivered to an ADC pin during sampling.

The 'charge time' naming comes from the fact that it can be controlled by external triggers and used to measure intervals between those triggers by measuring the amount of charge delivered to a known capacitor.

Instead, by delivering a known current over a known interval, we can apply a fixed amount of charge, and with the equations shown in Fig.3, we can measure capacitance.

That means we don't need to resort to complex calculations involving logarithms which are often needed to analyse RC circuits.

The 8-bit PIC devices we used for the earlier *Tweezers* avoided logarithms by using an approximation and limiting the state of charge to regions where the approximation would be most accurate.

For this test, R_d is connected to ground and R_a is connected to the CTMU current source. An initial ADC sample is taken, followed by a second sample after a known interval, with the current source active between the two samples.

In both cases, 1kΩ series resistors are used. This is because the resistors will drop some voltage due to the current flowing, and the 1kΩ resistors will drop the least voltage. Fortunately, it will be the same for the first and second readings, so it will cancel out.

Five different currents can be applied, so we can take multiple readings. To extend the range further, shorter and longer durations are used, giving six readings over different orders of magnitude.

Like the resistor measurement, the readings near the middle of the range are chosen. High readings are ignored as the current source tends to saturate as its output nears the supply voltage. That would result in inaccurate readings.

Since the voltage is the denominator of the equation, lower values are disregarded because this will diminish the resolution. Higher values lead to closer steps between their respective reciprocals and thus better resolution.

The capacitance calculation depends on the supply voltage, CTMU current and time, so the expected accuracy is not as good as for resistance or diode voltage. Still, with calibration, it should be within 5%.

Between measurements in the resistor and capacitor modes, the 1kΩ resistors in each group are pulled low, and the remaining pins are left floating. Apart from minimising current flowing in or out of floating pins, this also serves to discharge any connected capacitor, so it is ready for the next measurement cycle.

One exception is in diode mode. In this case, the CON+ terminal is pulled high instead of low to provide a bias to light an attached LED, allowing it to be visually checked. A light-emitting diode connected in the forward direction will illuminate except for the period when the reading is done, when it will appear to flicker off briefly.

Scope and meter modes

Another arrangement is used for the scope and meter modes that allows them to read voltages outside the *Tweezers*' supply rails. Four more 1kΩ resistors are put into play. Of each pair, one is pulled high at the micro end and the other low. This situation

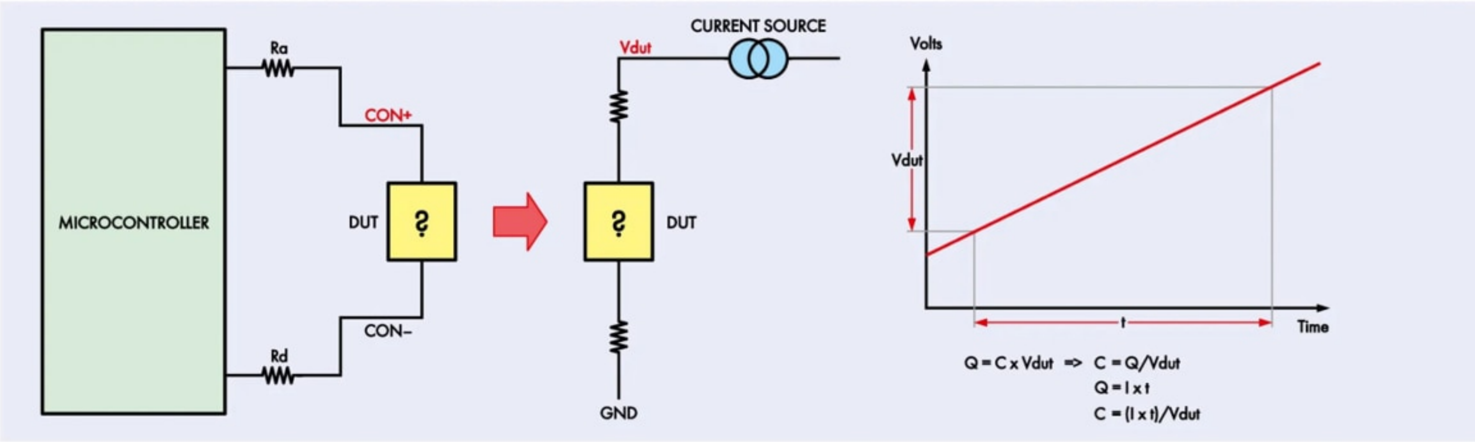
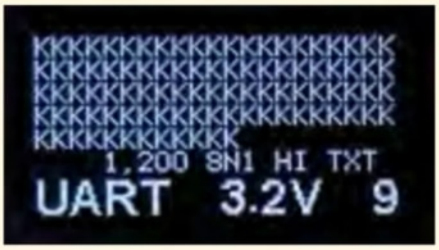
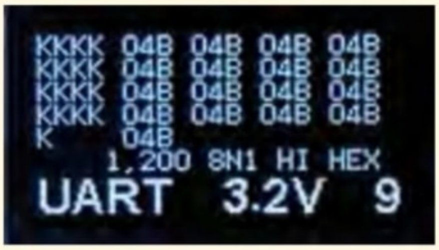


Fig.3: the constant-current source of the CTMU peripheral greatly simplifies the measuring of capacitances. It eliminates the need for the processor-intensive logarithmic calculations needed to derive a capacitor value from the time constant of an RC circuit.



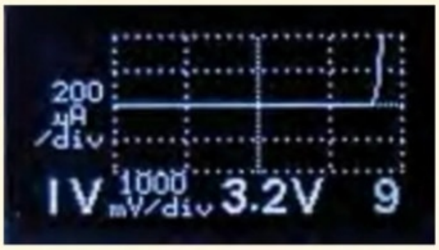
```
KKKKKKKKKKKKKKKKKKKKK
KKKKKKKKKKKKKKKKKKKKK
KKKKKKKKKKKKKKKKKKKKK
KKKKKKKKKKKKKKKKKKKKK
KKKKKKKKKKKK
    1,200 SN1 HI TXT
UART  3.2V  9
```

Screen 16: we find the UART Serial Decoder indispensable at times. Like the Scope mode, it is highly configurable in terms of baud rates, bit depth and data polarity. This shows the TXT view.



```
KKKK 04B 04B 04B 04B
KKKK 04B 04B 04B 04B
KKKK 04B 04B 04B 04B
KKKK 04B 04B 04B 04B
K    04B
    1,200 SN1 HI HEX
UART  3.2V  9
```

Screen 17: the Serial Decoder also offers a hexadecimal mode, useful for seeing binary data and control codes. Framing or parity errors are shown, which can help you to determine the data format.



Screen 18: while Diode mode cannot report dual diodes such as bicolour LEDs, the I/V Plotter shows both polarities. The current and voltage scales can be zoomed in for more detail.

is shown on the left of Fig.4, with the simplified circuit to its right being functionally equivalent.

Each tip is thus subjected to a 20:1 voltage divider biased to half the supply voltage. Readings are taken by measuring the difference in the voltage between V1 and V2 and multiplying by 21. With a nominal 3V supply, we can measure up to around 30V (differential) between CON+ and CON–. Biased differential inputs allow positive and negative voltages to be measured.

It's possible for current to flow through the unused 1kΩ and 100kΩ resistors if the applied voltage is greater than the supply voltage. The current through the 1kΩ resistors is shunted to the supply rails by D1 and D2. The 100kΩ resistors will conduct much less current, and this will flow through the microcontroller's internal protection diodes.

These unwanted currents dictate the useful upper voltage limits of the scope and meter modes. Voltages beyond those limits could cause damage to the microcontroller.

Damage could also occur if excess voltage is applied while the pins are being driven (as for resistor, capacitor and diode modes), since these currents will now flow through the chip's internal output transistors instead of the external and internal protection diodes.

We found that one of our earlier prototypes was running cells flat even when not being used; this was because the damaged microcontroller was drawing excess current in sleep mode. If you find your *Tweezers* are going through cells excessively, that could be why.

So care must be taken only to apply higher voltages in modes when the *Tweezers* concern with the older *Tweezers* designs, as they did not have any modes to measure externally applied voltages, and were only designed for use with passive devices.

Modes that expect digital signals, such as the logic analyser and serial decoder, simply pull CON– to ground via its 1kΩ resistor. CON+ may be left floating or weakly pulled up or down by the 100kΩ resistor to detect the difference between high, low and high impedance logic levels.

Firmware

The firmware program on IC1 is responsible for initialising all the peripherals and the OLED display. It coordinates the measurements, reads the pushbuttons and controls the display as needed.

Apart from the main program loop, a timer interrupt is set to fire about three times per second, triggering display updates at a comfortable rate.

The code is modular, and each of the individual modes is much like a self-contained program that is called upon during the program loop. Each makes the measurements it needs and displays the results.

The buttons are checked and flags are set for each mode to process in accordance with its operation.

Power consumption

The processor runs at a modest 4MHz instruction clock (down from the maximum possible 16MHz) to minimise power consumption and thus, the load on the coin cell. We could not maintain the desired screen update rate at lower speeds than this.

During some of the scope mode's sample periods, the clock is sped up to 16MHz to allow faster ADC sampling rates. There are also periods where no urgent processing is needed,

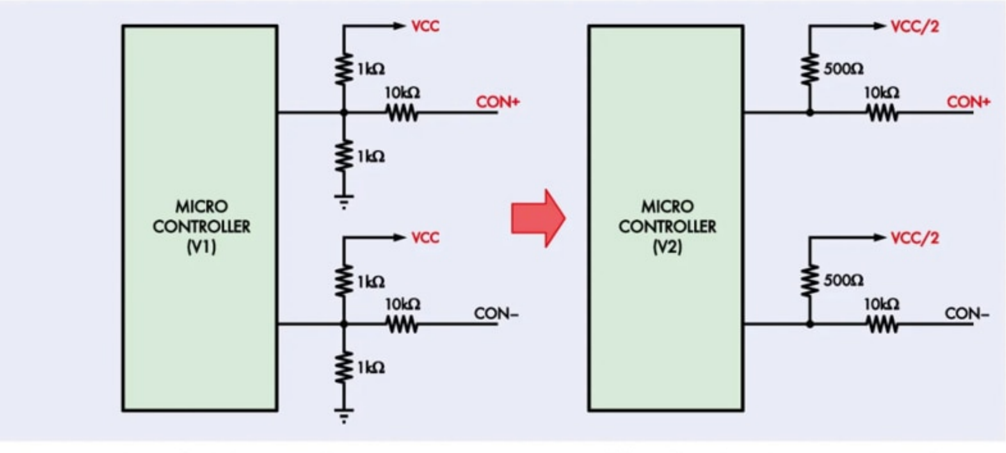
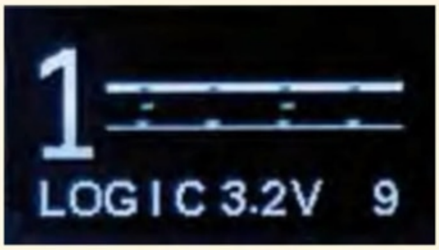


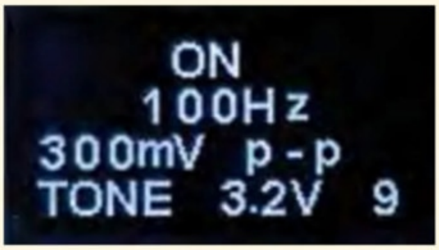
Fig.4: the Meter and Scope modes use a set of four fixed resistors to provide a biased divider capable of measuring voltages above and below the Advanced Tweezers' supply rails. The circuits on the left and right are equivalent.

With three pushbuttons, calibrating and changing modes is much easier than earlier version of the Tweezers.

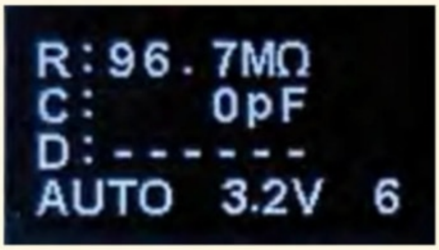
Screengrabs from part two, showing the Advanced SMD Test Tweezers in operation


1
LOGIC 3.2V 9

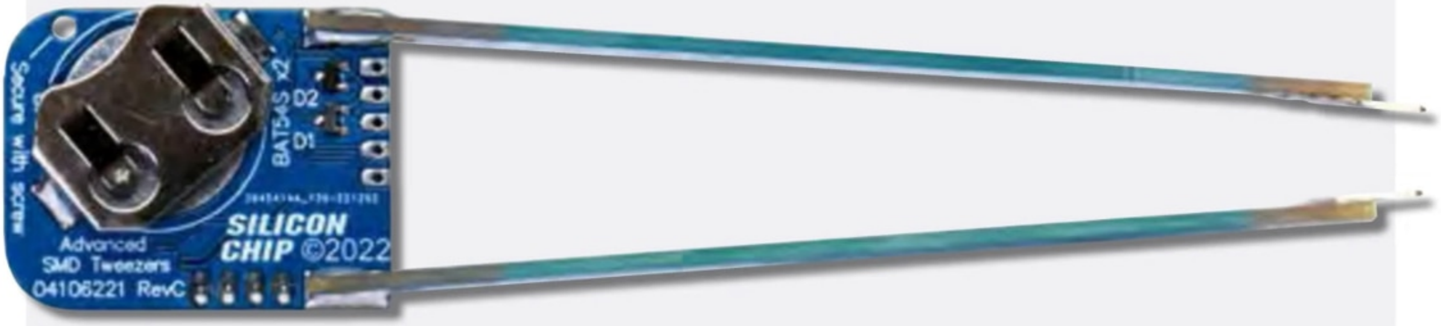
Screen 19: the Logic Analyser shows whether it detects a high, low or high impedance logic level. A scrolling chart also shows a brief history, making it easier to see transients and repeating patterns.


ON
100Hz
300mV p-p
TONE 3.2V 9

Screen 20: like Scope mode, the Tone Generator is handy at audio frequencies or as a simple clock generator. It can produce square waves at five different frequencies and four different amplitudes.


R:96.7MΩ
C: 0pF
D:------
AUTO 3.2V 6

Screen 21: the Auto screen is only one of ten pages but encompasses and surpasses the abilities of its predecessors. It shows resistance, capacitance, diode polarity and forward voltage.



The hole at upper left is for a Nylon M2 screw to prevent children from removing the coin cell. While it would be quite difficult for them to remove it anyway, we want to ensure it is safe.

in which case the DOZE feature is activated. The processing core runs at an even lower fraction of its maximum speed, reducing power usage even further.

There is a timer counting off the timer interrupt. When this expires, a routine is called to power off the OLED and put the peripherals and I/O pins into a low-power state, after which the processor goes into the lowest-power SLEEP state.

By completely powering off the OLED, we avoid any possibility that it is not in its lowest possible power state. The OLED modules we used in the earlier *Tweezers* have a sleep mode that initially appears quite effective but sometimes had a current draw that crept up higher than we expected.

Interrupts triggered by a change in the switch states are used to wake up the processor while it is stopped. It resumes by doing much the same as when it first initialises, since the peripherals have all been put into low-power modes too.

The SLEEP mode keeps the RAM contents, so resuming from sleep will thus retain all the same mode settings and parameters.

Our measurements during SLEEP recorded a consistent current draw around 700nA, much lower than the earlier *Tweezers* variants. At these levels, the cell's self-discharge is likely to be more significant than the actual circuit current.

We also sought to minimise current draw during normal operation; this is typically in the single-digit milliamps, depending on the operating mode. This is critical, as the amount of usable capacity for a coin cell (as measured in mAh) is higher with a lower current draw.

So higher consumption not only reduces the time that a given cell capacity can be used, but also tends

Parts List – Advanced SMD Test Tweezers

1 double-sided main PCB coded 04106221, blue (28 × 36mm) *
2 double-sided arm PCBs coded 04106212, blue (100 × 8mm) *
3 gold-plated header pins (for tips and OLED support)
1 PIC24FJ256GA702-I/SS microcontroller programmed
with 0410622A.HEX (IC1) *
1 0.96in 128×64 I^2C OLED module, blue/cyan or white (MOD1)
2 BAT54S dual series schottky diodes, SOT-23 (D1, D2)
2 100nF 50V X7R ceramic capacitors, SMD M2012/0805 size
1 10μF 6V X7R ceramic capacitors, SMD M2012/0805 size
2 100kΩ ⅛W 1% SMD resistors, M2012/0805 size
3 10kΩ ⅛W 1% SMD resistors, M2012/0805 size
6 1kΩ ⅛W 1% SMD resistors, M2012/0805 size
3 small SMD two-pin tactile switches (S1-S3)
1 surface-mount 32mm coin cell holder (BAT1)
2 100mm lengths of 10mm diameter clear heatshrink tubing
1 5-pin right-angled header, 2.54mm pitch (CON1; **optional**, for ICSP)
1 label (**optional**; see Fig.8 next month)
1 M2 × 6mm Nylon screw
2 M2 Nylon nuts
1 CR2032 or CR2025 lithium coin cell

* *We will provide details for purchasing these items in Part 2 next month*

9.88kΩ
RES
3.2V
7

Screen 22: the Res screen provides the same resistance information as the Auto screen but in a larger font, which is handy for checking and sorting through different resistor values.

1.01µF
CAP
3.2V

Screen 23: the Cap screen works similarly, displaying just the measured capacitance in large text. It's perfect for working out which part is which among a pile of unmarked SMD capacitors.

1.78V
DIODE
3.2V
5

Screen 24: the diode screen is similar to the Diode display on the Auto screen but a bias is applied from CON+ to CON– between tests. This lets you quickly check the polarity and operation of LEDs.

to reduce that capacity. The internal resistance of a coin cell is of the order of 20Ω, so a current in the milliamps will also reduce the voltage available to the circuit by a noticeable amount, around 0.1V.

Apart from its internal controller, the OLED only draws current for lit pixels, so there is the option to adjust the brightness and thus compromise between visibility and power consumption. The OLED is typically the greatest drain on the battery.

The OLED dictates the 2.4V minimum voltage as it tends to fade and flicker below that level. The microcontroller will work down to around 2V, but running this low also limits the effective sampling range of the ADC.

We initially used a pretty thick font for some of the displays. By changing to a lighter font with thinner strokes, we reduced the current by over 3mA in some modes!

We found that the display was perfectly visible indoors at a reduced brightness, so we have set the default brightness to be somewhere in the lower end of its range, prolonging cell life and reducing the voltage drop. You can increase the brightness via the settings if necessary, eg, for use in very brightly lit areas.

Next month

Because this is a reasonably complicated instrument (at least in terms of its modes and features), we don't have space in this issue for the full construction, calibration and usage details. That will all be covered in the final article next month. Some screengrabs showing the *Tweezers* in operation are shown above.

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HIGH-PERFORMANCE ACTIVE SUBWOOFER FOR HI-FI AT HOME

PART 2: BY PHIL PROSSER

Last month, we showed the performance of the new ultra-high-fidelity Subwoofer design and provided all the cabinet construction details.

In this second and final article in the series, we'll finish off the Active Subwoofer by building and installing its internal 180W amplifier, finishing the wiring, installing the driver and adding some feet.

After building the SC200, Ultra-LD Mk.3 or Mk.4 amplifier, most of the remaining work is in making the custom metal bracket, drilling the heatsink and combining the bracket, heatsink, amplifier and power supply into a compact amplification module. It then slots neatly into the 220 × 170mm rectangular cut-out that you would have already made in the rear of the *Subwoofer*.

If you haven't already built the amplifier module, it's best to refer to the 'IMPORTANT!' box opposite (repeated from last month).

You will also need to build the *Multi-Channel Speaker Protector* but with only one relay. You can also leave off the components surrounding the missing relay. For example, you could install RLY2 and leave off everything to the left of diode D2 and the 100kΩ resistor above it.

With those two modules assembled, and the rest of the components gathered, you are ready to start putting it all together.

Fabricating the bracket

I used a 3mm-thick panel of aluminium as the main plate for the chassis. To that, I mounted a folded bracket made from 1.5mm-thick aluminium for the transformer and an L-shaped panel for the speaker protector.

You can see these panels assembled in Photo 11 (note some differences in the cut-out from the final version). All of the plate amplifier parts mount to those panels, mainly the central bracket.

I used nutserts to hold those pieces together as they make for an elegant result (they're basically threaded rivets). However, you can use machine screws and nuts instead.

The L-bracket for the *Speaker Protector* can be made by bending an aluminium sheet by hand in a vise. The larger bracket for the power supply is trickier; if you do not have access to metal folding equipment, I saw some brackets at our local hardware store that would work. Just remember that the power supply transformer is a heavy component and the mounting needs to consider shock loads such as being dropped.

The power supply is straightforward; its circuit diagram is shown in Fig.14. Mains power comes in via CON1 and passes through fuse F1 and power switch S1 to transformer T1 (which may have a single 230V or dual 115V primaries, depending on which transformer you purchase). Its two 40V AC secondaries connect to bridge rectifier BR1 and a capacitor bank, producing ±57V DC rails.

Since a subwoofer must deliver large amounts of power for extended periods,

IMPORTANT!

What you need to build the *Active Subwoofer.*

First and foremost, you need the 'active' element – an amplifier.

At the time of publication this was more complicated than expected. We intended to use the upgrade to the *Ultra LD Mk.2 200W Power Amplifier* published back in August 2010 with the *Mk.3* (or its surface-mount follow-up, the *Mk.4*). However, unfortunately, the 'pandemic silicon shortage' is still affecting a few critical devices for those designs, so they will be published at a later date. Instead, we suggest you use the *SC200 200W Amplifier Module* we published back in 2018 (January to March).

That circuit incorporates most of the features of modern amplifier modules, but uses easy-to-solder through-hole components. There are no tiny surface-mount components.

Do note that just like the *Ultra-LD Mk.3* and *Mk.4* there are component issues for the *SC200*. Fortunately, we have found good alternatives – see the box last month.

You will also need the *Multi-Channel Speaker Protector* (4-CH) from *PE,* January 2023, timber for the cabinet and acoustic wadding.

we have 16mF of energy storage per rail. This reflects the 'no compromise' approach to the design. However, if you only install two 8000µF capacitors, it will still work reasonably well.

The 270Ω 10W resistor is to drop the voltage to a level suitable for powering the *Speaker Protector* and also to reduce the dissipation in its regulator.

Plate amplifier construction

I mounted the (*Ultra-LD*) amplifier to the main panel and heatsink combined. In other words, the 3mm base plate is between the output devices and the heatsink. You can see the arrangement in Photo 12.

Provided your main panel is free of dents and scratches and the heatsink is mounted to this with a good layer

Photo 11: The majority of the plate amplifier parts mount on this bracket.

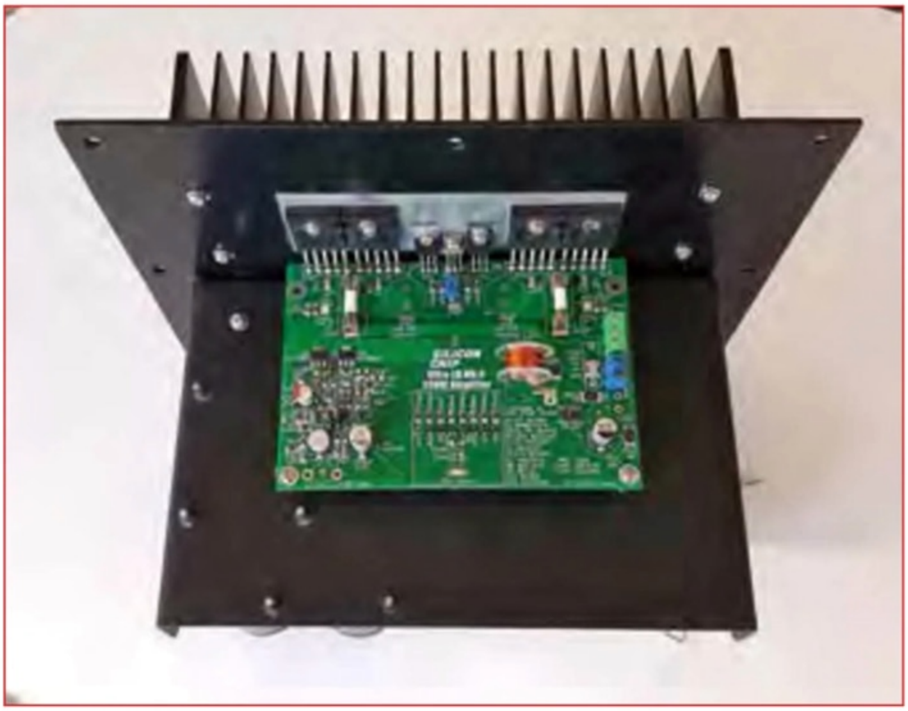


Photo 12: Here, the Ultra-LD Mk.4 amplifier attached to the bracket, ready to be wired up – you can also use the Mk.3 or the easier SC200.

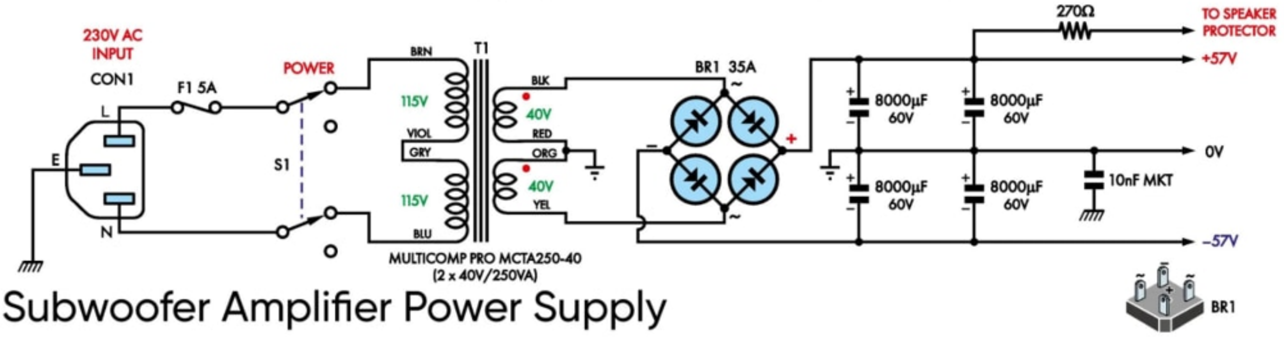

230V AC INPUT
CON1
L
E
N
F1 5A
POWER
S1
BRN
T1
115V
VIOL
GRY
115V
BLU
BLK
40V
RED
ORG
40V
YEL
MULTICOMP PRO MCTA250-40
(2 x 40V/250VA)
BR1 35A
~
–
+
~
8000µF 60V
8000µF 60V
8000µF 60V
8000µF 60V
10nF MKT
270Ω
TO SPEAKER PROTECTOR
+57V
0V
–57V
BR1
Subwoofer Amplifier Power Supply

Fig.14: the subwoofer power supply is about as basic as it gets. I used a 300VA transformer, but it is no longer available, and 250VA is adequate.

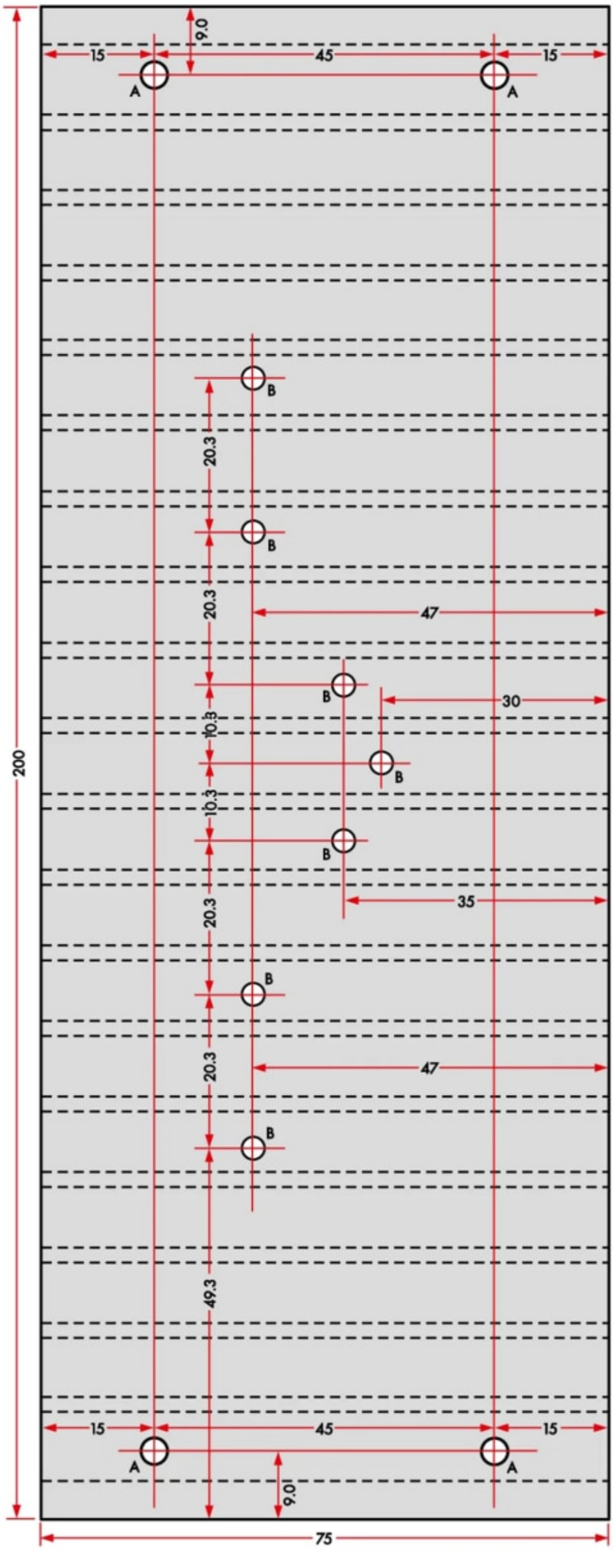
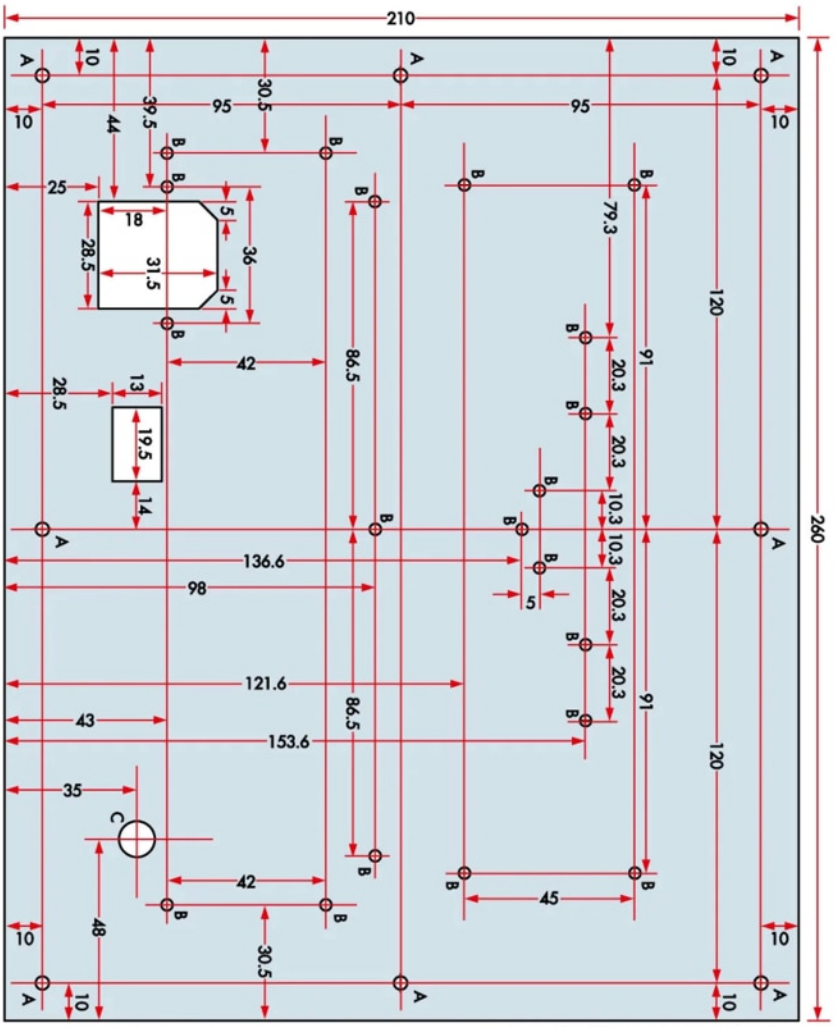


Fig.15 (left): the heatsink drilling details. The heatsink used is the same as in the original Ultra-LD Mk.3/4 articles, but the way the heatsink is mounted is different. These hole positions are suitable for any of the amplifier modules mentioned, including the SC200.

Fig.16 (below): the rear plate for the amplifier is made from 3mm-thick aluminium cut and drilled, as shown here. It's a good idea to paint it black when finished. Ensure the rectangular hole for the rocker switch is only as large as it needs to be for the switch to snap in. Again, this is for the Ultra-LD amplifier, but it will work fo the SC200.



HOLES A: 3.5mm DIAMETER
HOLES B: 3.0mm DIAMETER
HOLE C: 9.5mm DIAMETER

PANEL SHOWN HERE AT 50% FULL SIZE

ALL DIMENSIONS IN MILLIMETRES

←(Viewed from flat mounting side)

of thermal paste, this will make fabrication easier and contribute to the overall heatsinking capacity.

To ensure perfect alignment of the baseplate and the heatsink mounting holes to the transistors, I drilled and assembled the heatsink and main panel before building the amplifier and then mounted the transistors to that before soldering them to the PCB. This ensured that the transistors were perfectly aligned to the mounting holes and PCB.

Do not use insulators at this point; we will add them later. Once you have soldered the transistors in like this, you can pull everything apart, knowing it will fit perfectly later on.

Heatsink drilling

Fig.15 shows where to drill the holes in the heatsink for the (*Ultra-LD*) amplifier. My approach was to mark all holes on the main panel first (see Fig.16), then drill and tap the four corner mounting holes into the heatsink and attach it to the main panel with M3 screws. I then drilled 2.5mm holes through the main panel *and* heatsink. This guarantees that the transistor mounting holes are perfectly aligned between both panels.

I then took the heatsink off, tapped and deburred the holes in the heatsink, then drilled and deburred the main panel holes to 3.5mm.

Details of the main bracket that attaches to the rear panel and holds the amplifier module and power supply are shown in Fig.17.

The speaker protector bracket attaches via two of the heatsink mounting screws. This is fabricated from 1.5mm aluminium sheet folded at 90°; see Fig.18 for the details. I included a small clamp to hold the 270Ω 10W wirewound resistor to drop the 57V rails by about 15V. It is wired in series with the positive supply to the *Speaker Protector* module.

Once the metalwork is ready, dry-fit everything first and get your assembly plan in mind. Use Figs.19-21 and Photos 12-14 to see how everything fits. At this point, temporarily fit the amplifier board, screw the output devices to their mounting positions without insulators and solder the output devices to the PCB. This gets all the holes lined up.

Start final assembly with the terminal block, the transformer, earth screw and diode bridge. Use a small amount of thermal paste under the diode bridge. Install 15mm standoffs for the amplifier module (only in the two corners furthest from the heatsink), making sure you countersink the hole for the screw that goes under the transformer and use a countersunk head screw. Cut a piece of Presspahn or similar and place it under the terminal

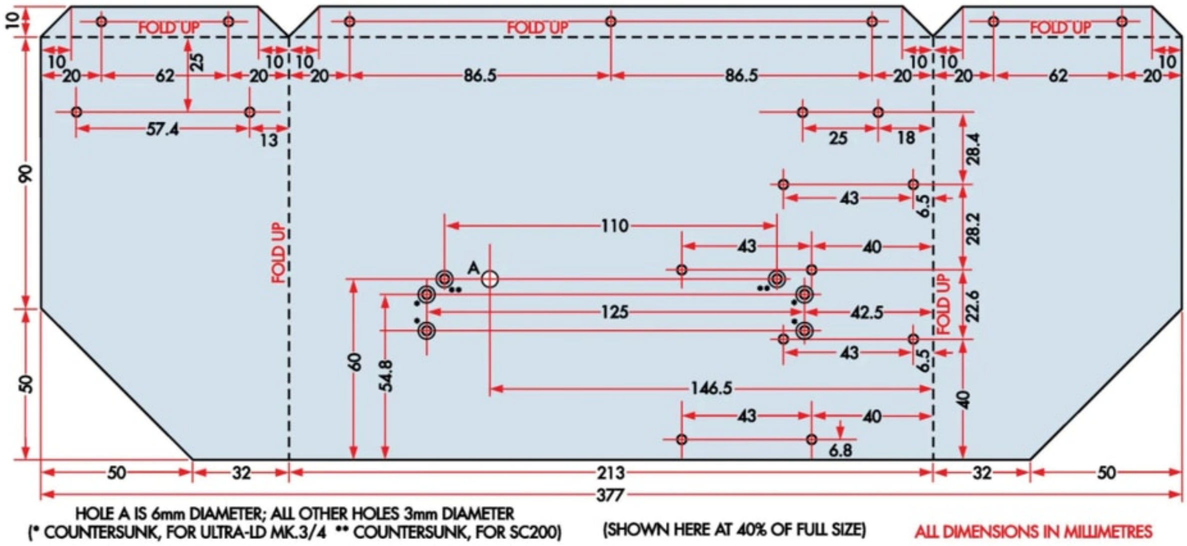
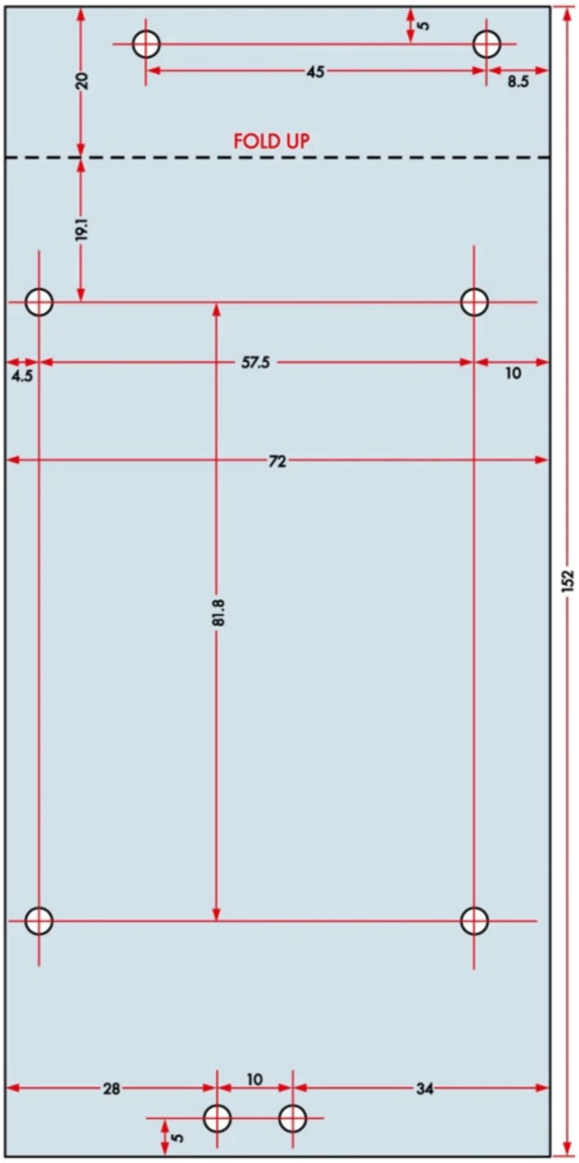
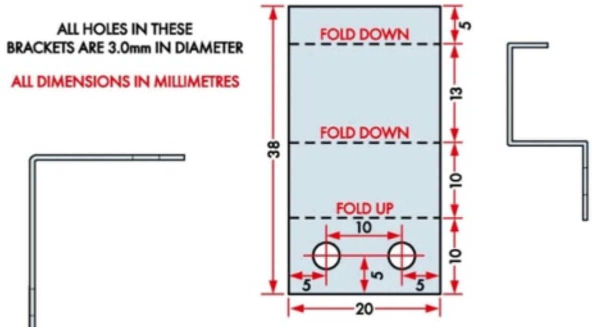

FOLD UP
FOLD UP
FOLD UP
FOLD UP
FOLD UP
10
20
62
25
20
10
10
20
86.5
86.5
20
10
10
20
62
20
10
57.4
13
25
18
28.4
43
6.5
28.2
110
43
40
A
125
42.5
22.6
43
6.5
60
54.8
146.5
40
43
40
6.8
90
50
50
32
213
32
50
377
HOLE A IS 6mm DIAMETER; ALL OTHER HOLES 3mm DIAMETER
(* COUNTERSUNK, FOR ULTRA-LD MK.3/4 ** COUNTERSUNK, FOR SC200)
(SHOWN HERE AT 40% OF FULL SIZE)
ALL DIMENSIONS IN MILLIMETRES

Fig.17 (above): and cut fold this support bracket from 1.5mm aluminium and paint it black. It attaches perpendicular to the rear plate. You only need to make two of the six countersunk holes, marked with a double asterisk for the SC200.

Fig.18 (below): the larger bracket allows the Speaker Protector to be mounted in the space next to the amplifier. The smaller bracket clamps down the 10W resistor needed to drop the supply voltage to the Speaker Protector.


5
20
45
8.5
FOLD UP
19.1
4.5
57.5
10
72
81.8
152
28
10
34
5


ALL HOLES IN THESE BRACKETS ARE 3.0mm IN DIAMETER
ALL DIMENSIONS IN MILLIMETRES
FOLD DOWN
FOLD DOWN
FOLD UP
38
5
13
10
10
10
5
5
5
20

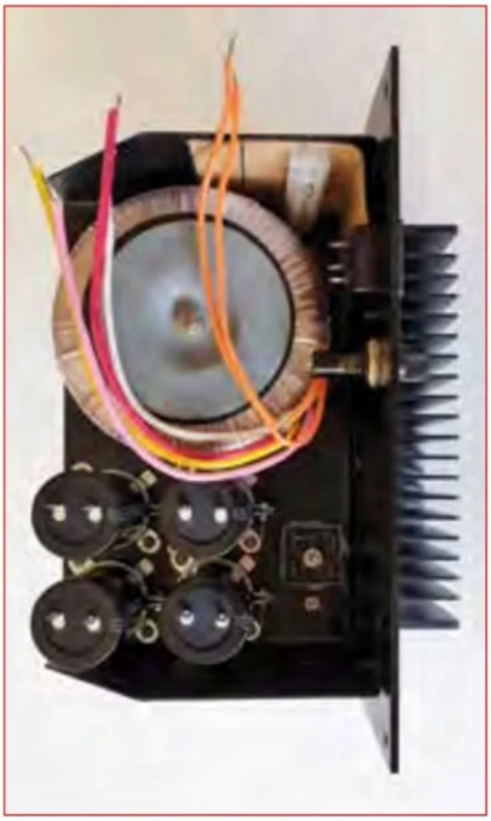


Photo 13: the underside of the plate amplifier with everything in place but not wired up yet.

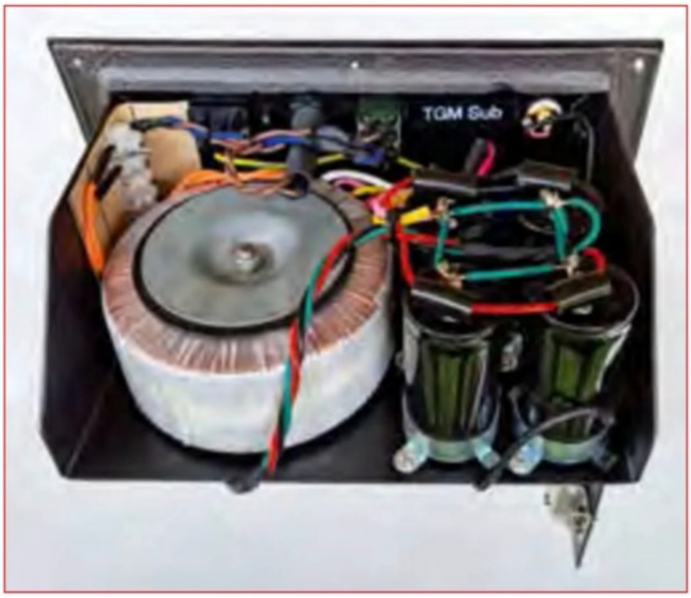
strip to ensure that if anything shakes loose from the terminal strip, there is insulation surrounding it. Make sure it is mounted far enough away from the rear panel that it won't interfere with the wiring to the IEC socket. It only needs to be a three-way terminal to connect the transformer primaries, including joining them in series.

Now mount the capacitors. Keep all the negative terminals facing the same way to ensure a tidy build. Then you can finally mount the amplifier module. Flip the module and fit the amplifier using insulating bushes and washers. Screw this down to the 15mm standoffs you installed earlier, using shakeproof washers under the M3 screws.

Next, install the *Speaker Protector* on its standoffs. Make sure you have connected a 200mm length of light-duty wire to the power input of the *Speaker Protector*, as this connector will be hard to get to later on.

Remember to wire the 270Ω 10W resistor in series with the power input for the *Speaker Protector*. This reduces power dissipation in the regulator heatsink on the *Protector*. This is not strictly necessary if you have a single relay installed, provided you use an th specified (Altronics H0655) heatsink on the *Speaker Protector*, but it doesn't hurt either.

Photo 14: A view of the underside of the completed plate amplifier, showing all the wiring. Note though that this version uses a separate fuse holder and a toggle switch; build yours based on the revised design with the fuse holder in the IEC socket.



With everything mounted, most of the remaining work is wiring it up, as shown in Fig.19 (mains wiring), Fig.20 (low-voltage supply wiring) and Fig.21 (amplifier module wiring).

Use 7.5A mains-rated cable for all power wiring and insulate all mains connections to prevent accidental contact with high voltages. Do note that the final design is slightly different than what's shown in the photos; instead of using a separate fuse-holder, we're using an IEC input socket with an integral fuseholder and the toggle power switch is replaced by a rocker switch. That simplifies the wiring and also keeps all the mains parts away from the low-voltage side. So follow the diagrams in that respect, not the photos.

You can use the following steps to guide you through the wiring.

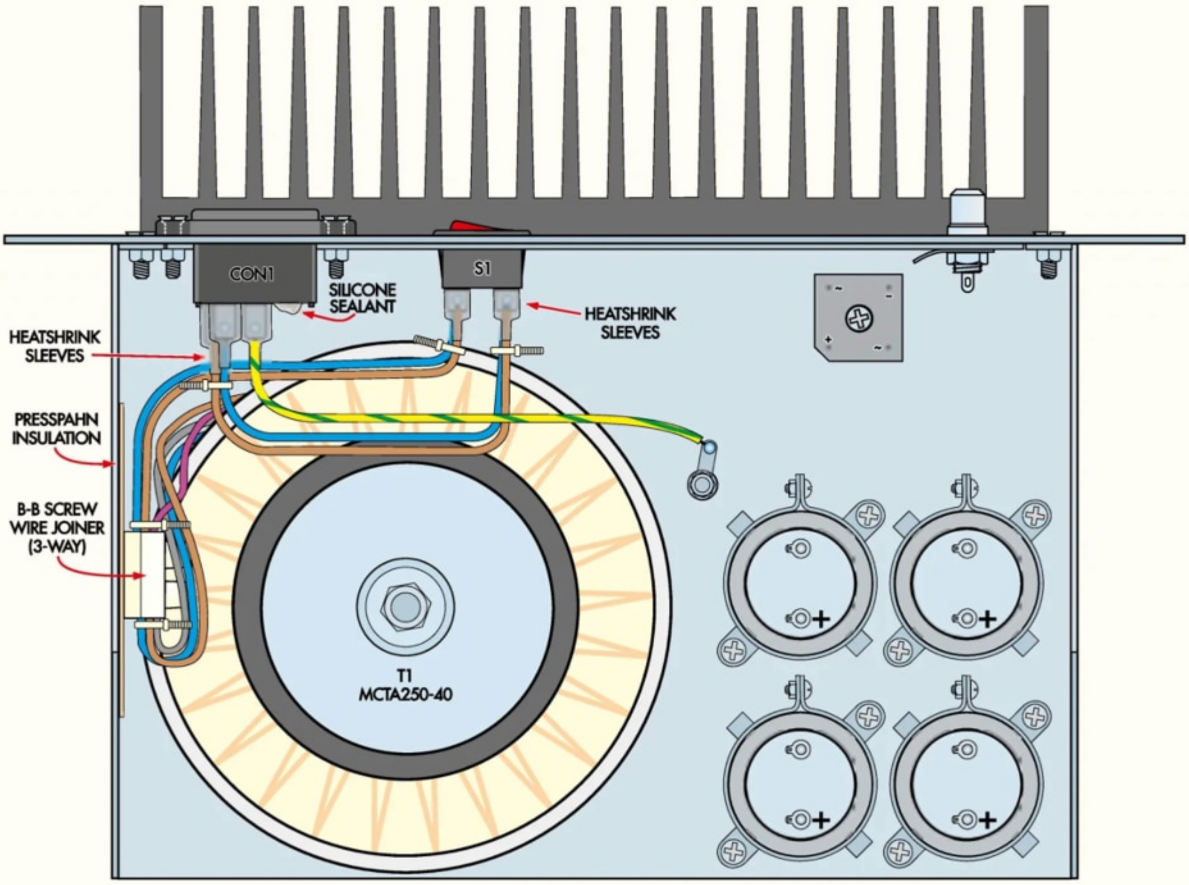


Fig.19: a view of the underside of the plate amplifier showing the mains wiring. Be sure to keep these wires short, tie them up and insulate all exposed mains junctions. When mounting the transformer, make sure it isn't too close to the corner or it could interfere with the IEC mains wiring; this configuration should be used rather than what is shown in the photos on the prototype as it keeps all the mains connections away from the lower-voltage side.

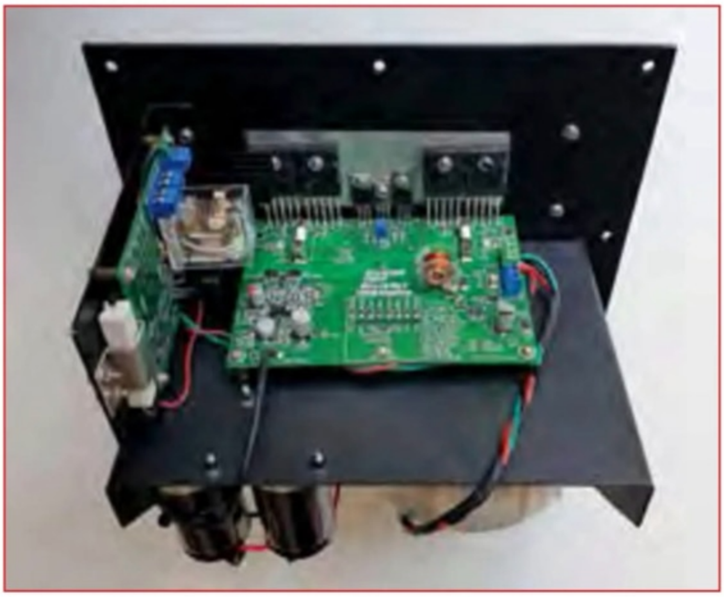


Photo 15: this is how the amplifier side of the module looks after construction and wiring is complete. Again, this shows the Ultra-LD Mk.4 amplifier – you can also use the Mk.3 or the easier SC200.

1. Install the earth lug and connect the green/yellow striped earth wire from a solder lug to the IEC plug mains earth *[we prefer using crimp eye terminals as, if crimped properly, they are more robust than solder joints – Editor]*. You can and should locate the earth lug right near the IEC socket; we've only shown it further away to avoid cluttering up the diagram.

   The earth screw must connect the earth lug to the chassis and nothing else. Ensure there is no paint or other layer stopping the earth lug from making good contact with the chassis; if there is, scrape it away.

   Connect the second solder lug to a 10nF capacitor and a short green wire from the capacitor to 0V on the capacitor bank.
2. Cut the transformer secondary wires to appropriate lengths to reach the bridge rectifier AC inputs. Crimp and plug or solder these to the bridge rectifier.
3. Using heavy-duty red and white wire, connect the bridge's positive and negative outputs to the capacitor bank. Optionally, use crimp connectors for the bridge.
4. Cover the exposed metal strip on the IEC socket with neutral-cure silicone sealant.
5. Using brown mains-rated wire, solder the live wire to the mains socket, and from there to one pole of the switch, then back to the terminal block. Make similar connections for neutral using blue mains-rated wire. Use heatshrink tubing to cover all exposed junctions. Twist these wires together and use cable ties to secure them, so that nothing can get loose should a connection fail.

We do not suggest using spade lugs to connect to the mains socket (except possibly for the earth) because space is relatively tight due to the proximity of the transformer. Ideally, the wires should be soldered so they extend upwards and over the transformer body to go to the switch. You shouldn't need to bend the IEC

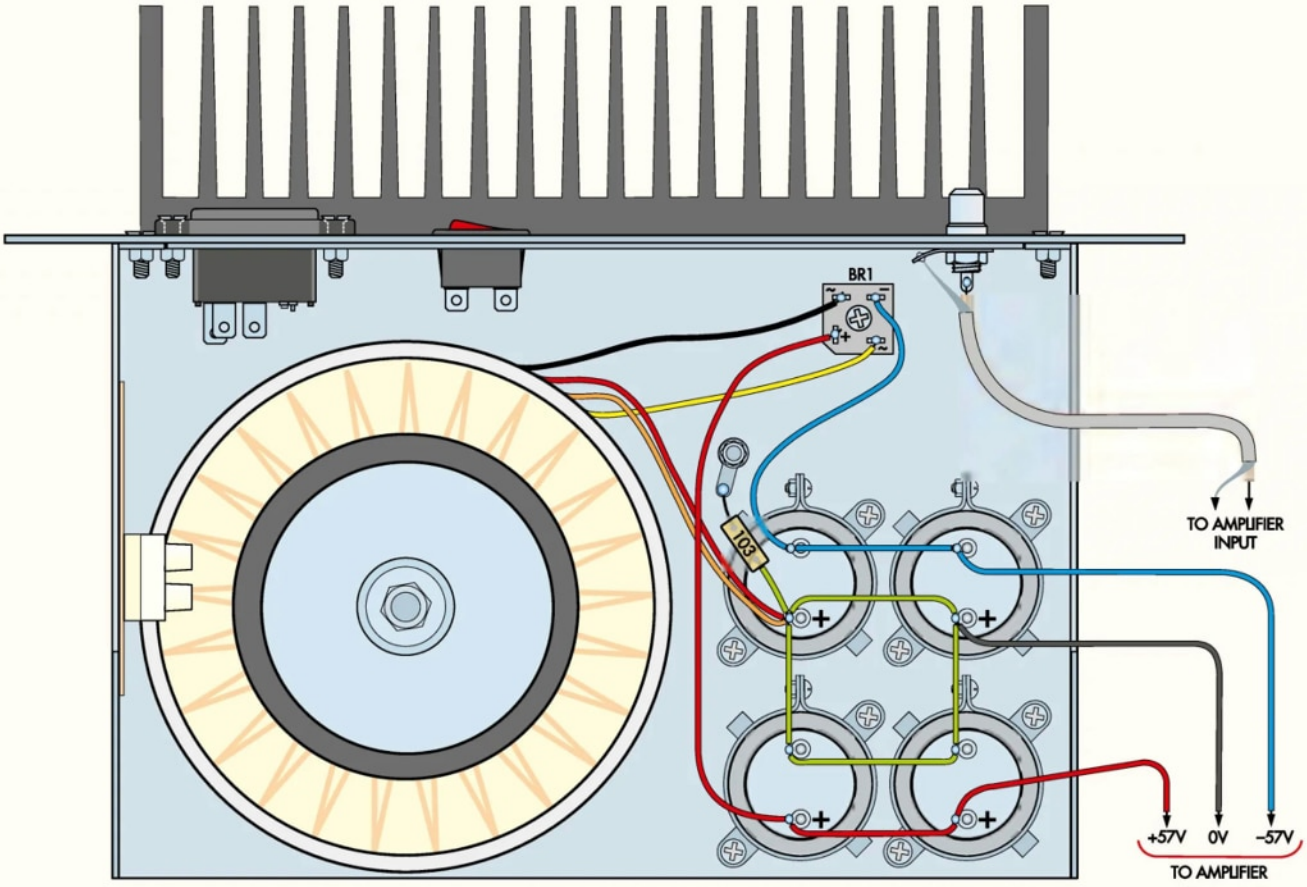


Fig.20: while similar to Fig.19, this diagram only shows the lower-voltage (~114V DC, so not that low) wiring for the power supply. It's best to follow this diagram exactly to avoid the possibility of ripple injection in the DC supply to the amplifier module.

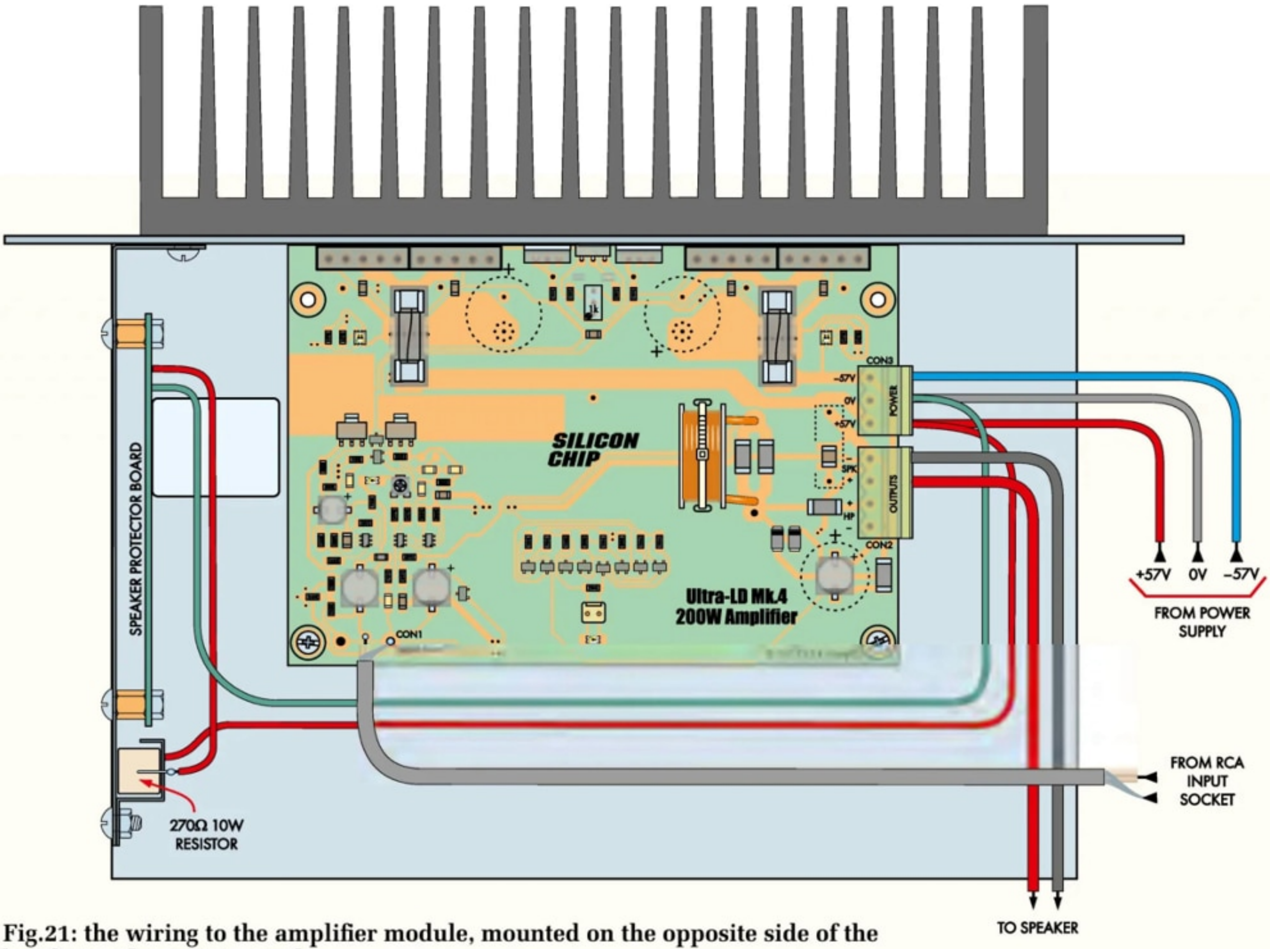


Fig.21: the wiring to the amplifier module, mounted on the opposite side of the bracket to the power supply.

socket lugs to get extra clearance but it could be done if necessary.

You could use crimp spade lugs to connect to the switch since it sits just above the transformer.

6. Connect the transformer primary winding to the switched mains on the terminal strip. Again, tie wrap these securely. If the transformer has two primaries, join the two windings in series via another terminal on the terminal strip (ideally, between the terminals used for the other primary connections).
7. Now wire up the capacitors using heavy-duty red and black wire. Join all the capacitor grounds together using heavy-duty green wire, and connect them to the transformer centre tap wires.
8. Next, take 400mm lengths of red, black and green heavy-duty wire and twist them together gently. Connect this to the +57V, –57V and ground terminals of the capacitor bank, respectively. Route this to the power amplifier power input and trim to length.
9. Use neutral-cure silicone sealant to stick pieces of plastic sleeving over the exposed ±57V connections on the capacitors at this point. This will save you from a potential (no pun intended) 114V DC shock if you slip and come across them.
10. Connect the +57V rail from the amplifier to the 270Ω resistor if you need this, and from the other end of the resistor to the positive input of the *Speaker Protector*. This can be done using light-duty wire.
11. Connect the amplifier ground to the GND input of the speaker protector.
12. Connect the amplifier output to the 'AMP' input on the *Speaker Protector*. The SPKR terminal goes to the positive side of the driver.
13. The amplifier ground output goes to the negative on the driver.

Photo 16: I used a staple gun to attach a double layer of poly wadding. This is required to dampen rear emissions from the driver and reduce resonances.

Final assembly

Assembly of the *Active Subwoofer* is very simple as all the work is in the enclosure and amplifier module. Install thick ply wadding on the sides, top and bottom of the enclosure as shown in Photo 16. Do not block the port as, when working hard, a lot of air is moving through it.

Connect the amplifier's output to the driver using heavy-duty speaker wire, being careful to connect the '+' output of the amplifier to the red terminal of the driver. Then install the amplifier module after sticking foam sealing tape around the edge of the hole in the cabinet. Attach the module with eight 16mm screws. Fig.22 and Photo 17 show how it should look when installed in the cabinet.

Last, fit the driver with foam tape around the hole with eight 16mm screws.

I stuck large felt feet on our *Active Subwoofer* to protect our floor. This thing is not a lightweight piece of kit!

Give your new *Subwoofer* a light workout to verify that everything is working as expected before you move onto earth-shaking bass!

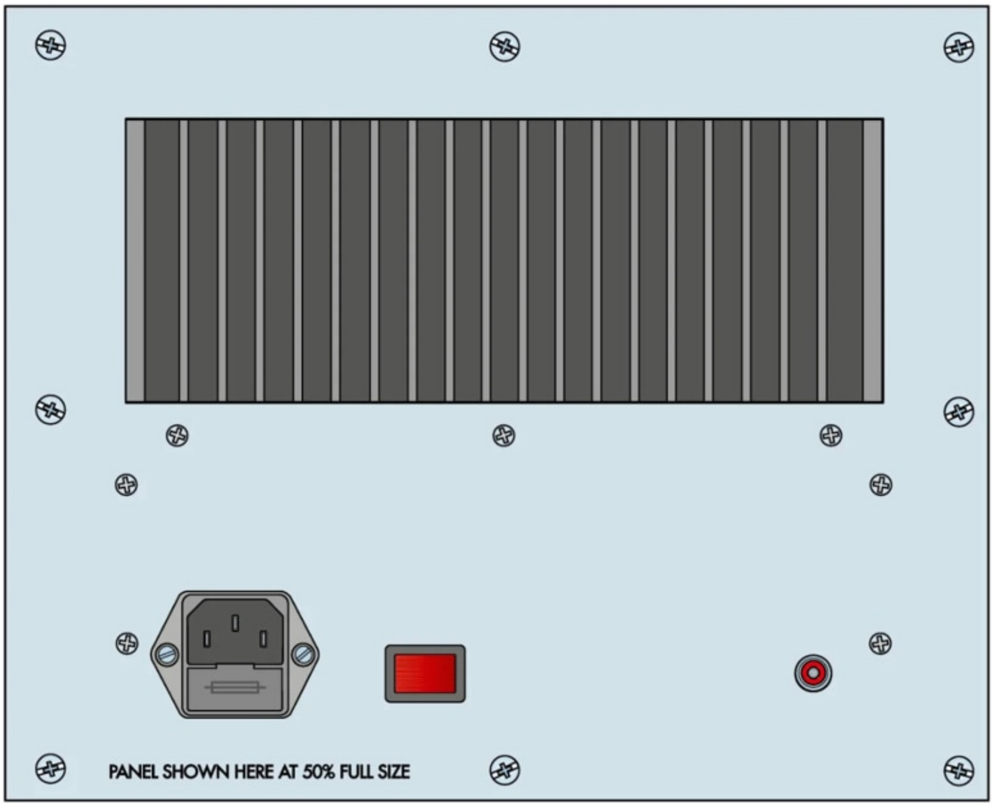


Fig.22: this is how the rear of the plate amplifier will look when you've finished.

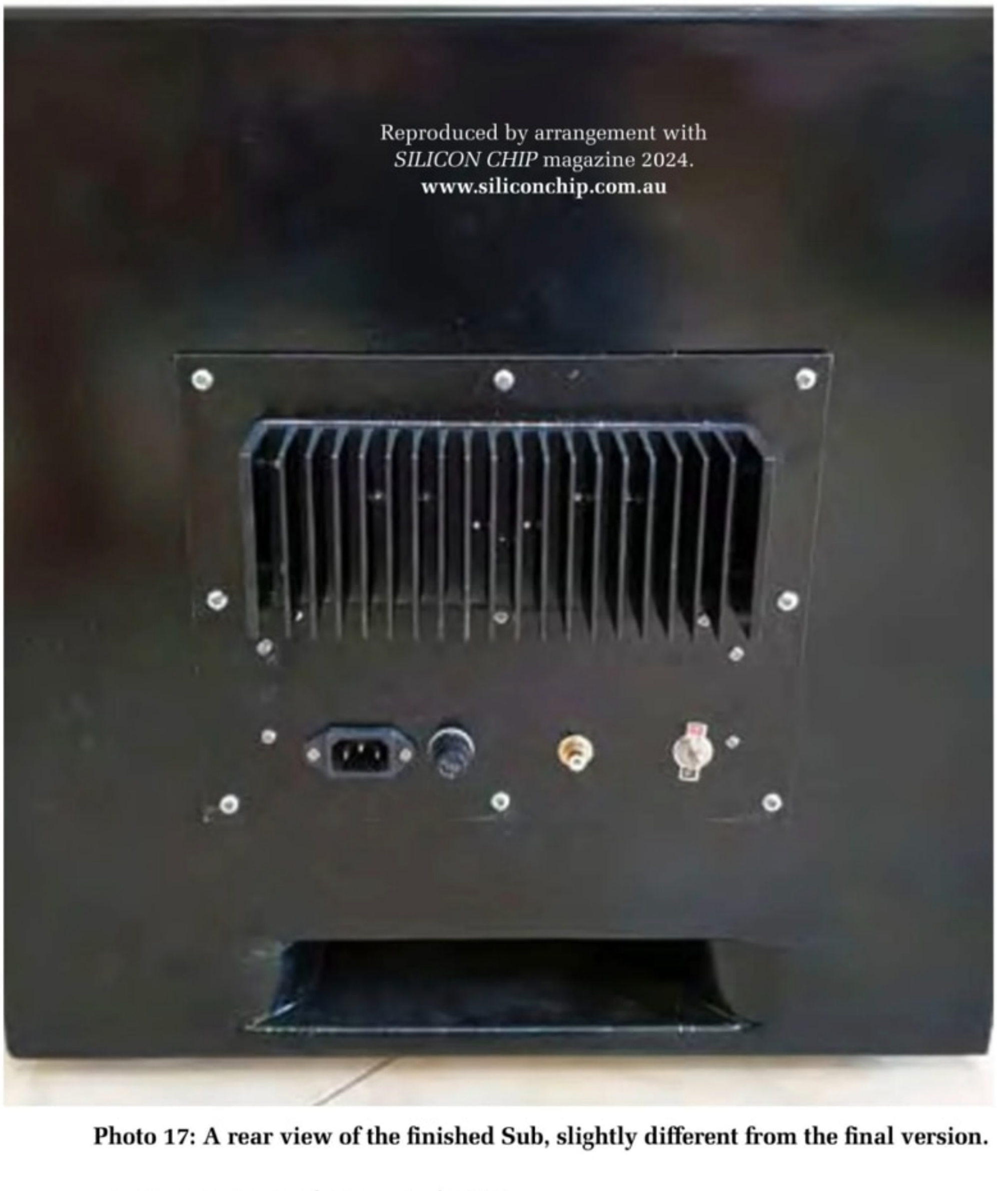


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Photo 17: A rear view of the finished Sub, slightly different from the final version.

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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 14

Well, hello there. May I be the first to say that you are looking particularly perspicacious and extraordinarily sagacious today. Now it's your turn to say something nice about me… there's no rush… I can wait…

Crumbs!

Thus far we've been performing all our experiments on a single breadboard. However, the time is drawing nigh (ie, in our next column) when we will need to use at least two of these little rascals, and it won't take you long to conclude that the phrase 'the more the merrier' applies.

Of course, the question you should be asking is, 'If we won't need multiple breadboards until next month, then why are you waffling on about them now?' That's a reasonable request and I'm glad you asked (although you didn't need to be so snarky about it). The reason for my waffling is that I just heard from my old friend Joe Farr, who hails from England and who spake as follows:

*Max, long story short, I'm designing a large breadboard for use with op-amps, which means I need three power rails: positive, negative and 0V. I usually buy standard 840-hole breadboards and stick them to a base board to make a larger breadboard. I've got several of these larger breadboards, so I can have multiple projects on-the-go at the same time. Breadboards are usually quite expensive, but I've just found these (***https://bit.ly/46RMRi2***) on CPC (part of Farnell, so a reputable company). They don't have the coloured power and ground rail lines, which is perfect because I'm going to add my own markings. They are only £1.70 each (£2.04 inc. VAT). That's peanuts. They are normally well over £7. The other thing that's nice is it's only a minimum £20 order for free delivery. I've just ordered 25 because they always come in handy, but the ones on eBay are all cheap imports and rubbish as the contacts deform as soon as you push a component lead in at the wrong angle.*

A few days later, Joe followed up to say that his breadboards had arrived. He went on to note: *They are nice and tight and good lead grabbers that (so far) look like they will last, unlike the inferior foreign ones that are made of 'tin'.* He closed by saying, the power and ground rails are cut in the middle, so you need to add jumpers. As you may recall, I made mention of this type of split-rail board in my *Arduinos and Solderless Breadboards* blog: **https://bit.ly/3NZ70uF**

The point is that this sort of deal won't last forever, especially once the word gets out (shhh!), so I would advise you to grab some of these bodacious beauties while the grabbing is good.

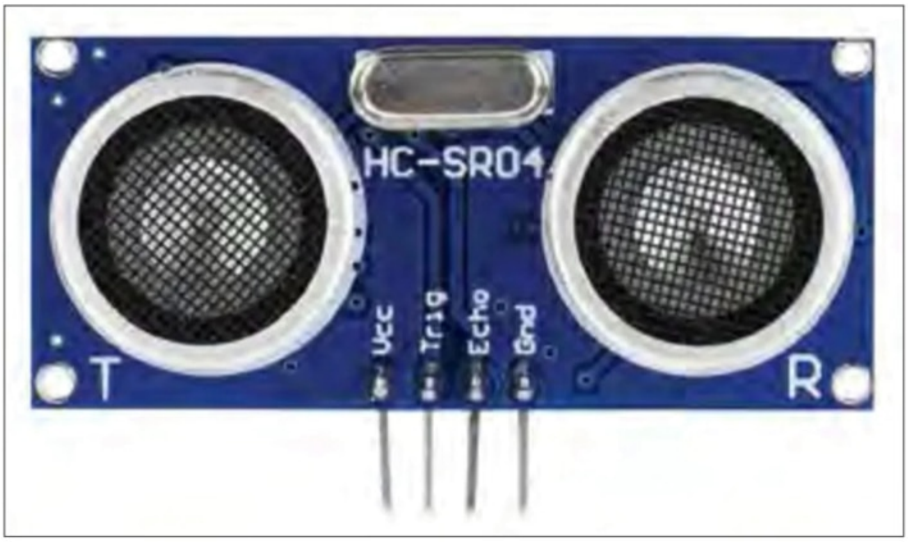


Fig.1. The HC-SR04 ultrasonic sensor.

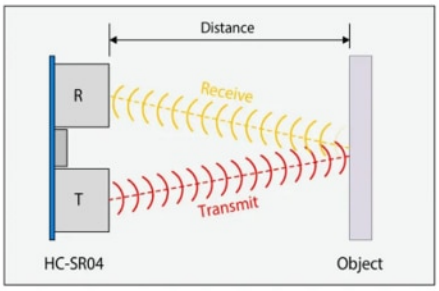


Fig.2. High-level, bird's eye view of HC-SR04 operation.

Bouncy, bouncy!

Much like the signals generated by the sensor we're going to play with in this column, I've been bouncing off the walls with excitement at the thought of what is to come. As you may recall, we closed our previous column (*PE*, January 2024) cogitating on the concept of how a bat 'sees' the world when using ultrasonic sounds for echolocation.

In our case, we're going to use the HC-SR04 ultrasonic sensor (Fig.1). This little beauty – which can measure distances from around 2cm (approx 1 inch) to 400cm (say, 13 feet) with an accuracy of 3mm (approx 0.1 inch) – is available from multiple suppliers, including Adafruit via Amazon: **https://bit.ly/49AMBq4**

A high-level view of the way this works is illustrated in Fig.2. The pinouts and waveforms for the HC-SR04 are shown in Fig.3 and Fig.4, respectively.

To be honest, I sort of made up the waveform traces shown in Fig.4 from bits and pieces I've gleaned on the interweb because I couldn't find a single source that pulled everything together in a way that didn't make me want to

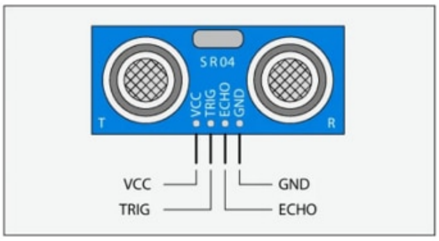


Fig.3. HC-SR04 pinouts.

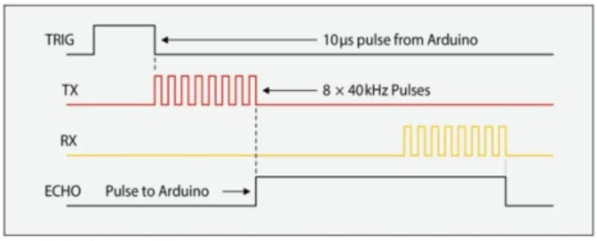


Fig.4. HC-SR04 waveforms.

gnash my teeth and rend my garb. I know we use the Arduino to apply a 10 microsecond (µs) positive-going pulse (⎍) to the SR04's `TRIG` ('trigger') input to set the ball rolling. Commencing on the *falling* edge of this pulse, the ultrasonic transmitter generates a series of eight 40kHz pulses.

What is the duration of this series of pulses? I don't know (sad face). I don't believe it matters because of the way (I think) things work (happy face). The SR04's `ECHO` output goes high at the end of the eight transmitted pulses. It stays high until the ultrasonic receiver 'sees' ('hears') the last of the eight reflected pulses. If there is no object in front of the SR04, and hence no reflected pulses, the SR04 will 'time out' and return the `ECHO` output to its logic 0 state after 38ms (milliseconds).

A modicum of math

In the case of sound passing through air, there are three interrelated parameters in which we are interested: distance, speed and time. Knowing any two of these parameters allows us to calculate the third. One way to visualise the relationship between these little scamps is by means of a handy-dandy magic triangle (Fig.5).

So, assuming we are using our SR04 ultrasonic sensor to measure distance, we need to know the speed of our ultrasonic pulses in air and the time they take to reach an object and return. Do we actually know these values? Well… sort of.

One thing we will know for sure is the duration of the pulse on the `ECHO` output. As we will see, this will be captured as an integer number of microseconds, but we'll come back to that in a moment. How about the speed of sound in air? Well, one piece of good news is that this is not dependent on the frequency of the sounds in question, which means a dog's bark, my squeals of delight, and ultrasonic pulses all travel at the same speed. More good news is that the speed of sound in air is not dependent on pressure (pressure and density both contribute to the speed of sound equally, but in opposition, and thus cancel each other out), which means my squawks of excitement will travel at the same speed, irrespective of whether I'm basking on a beach or moaning on a mountain.

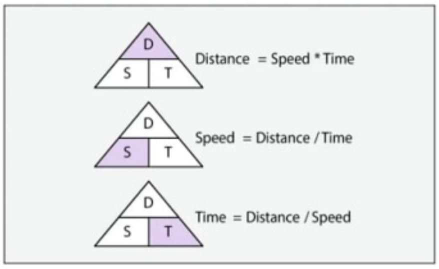


Fig.5. Magic triangle for distance, speed and time.

The bad news is that the speed in sound in air *is* affected by both temperature and humidity. If we assume dry air and a room temperature of 20°C (68°F), then the speed of sound is approximately 343 meters per second (m/s or ms^{-1}) or 1,125 feet per second (ft/s). To put this in perspective, that means sound travels more than the length of three football fields every second.

In a little while, we are going to use the Arduino's built-in `pulseIn()` function to measure the duration of the pulse on the SR04's `ECHO` output pin. This function accepts two arguments (well, it can accept three, but we are interested in only the first two for the purpose of these discussions): the number of the Arduino pin on which we want to read the pulse and the type of pulse we want to read – `LOW` (negative-going) (⊔) or `HIGH` (positive-going) (⎍). It returns a value in units of microseconds (µs), or 10^{-6} seconds.

Now, when we are using a formula like distance = speed * time, all the units must be compatible. That is, we don't want to be talking about distance in units of feet, speed in terms of furlongs per second, and time in units of jiffies in the same sentence (like wot I just did – oops!). Let's start by assuming we wish to measure our distances in units of centimeters (cm). In this case, 343m/s = 34,300cm/s. Now let's assume that we wish to employ time in units of µs. In this case, starting with 34,300cm/s and moving the decimal point six positions to the left gives us 0.0343cm/µs.

As an example, suppose our SR04 presented us with a pulse on its `ECHO` pin of 1.25ms, which will be presented to us as 1,250µs from the Arduino's `pulseIn()` function. Using distance = speed * time, this gives us a distance of 0.0343cm/µs * 1,250µs = 42.875cm.

Would this mean the object was 42.875cm from the sensor? The short answer is 'No!' The longer answer is that, in this particular scenario, the value returned from the `pulseIn()` function is associated with the round-trip time (RTT) for the pulses to travel from the SR04 to the object and back again. Thus, we would divide our 42.875cm result by 2 to give 21.4375cm, which would be rounded to 21cm if we are storing this value using the int (integer) data type.

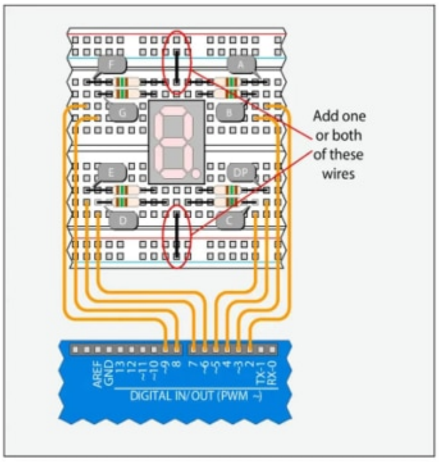


Fig.6. Returning the ground wires.

Izzy wizzy, let's get busy!

Older readers may remember *The Sooty Show*, which was created by the English magician, puppeteer, and television presenter, Harry Corbett. This childhood favorite was produced for the BBC from 1955 to 1967, and then for ITV from 1968 until 1992. Harry was the presenter from 1955 until he passed in 1975, at which point his son, Matthew, took over the reins. The main characters (apart from the human presenter) were Sooty (a bear), Sweep (a dog), and Soo (a panda). Sooty, who was kind-hearted but also a bit cheeky (much like your humble narrator at that time), had a magic wand, which responded to the words 'Izzy wizzy, let's get busy!' But we digress…

First, we need to clear some space on our breadboard. We're going to keep our 7-segment display and our piezoelectric buzzer along with any of their ancillary wires and components like current-limiting resistors. However, we're going to remove our transistor,

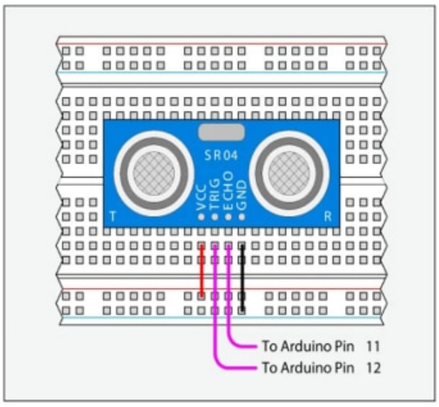
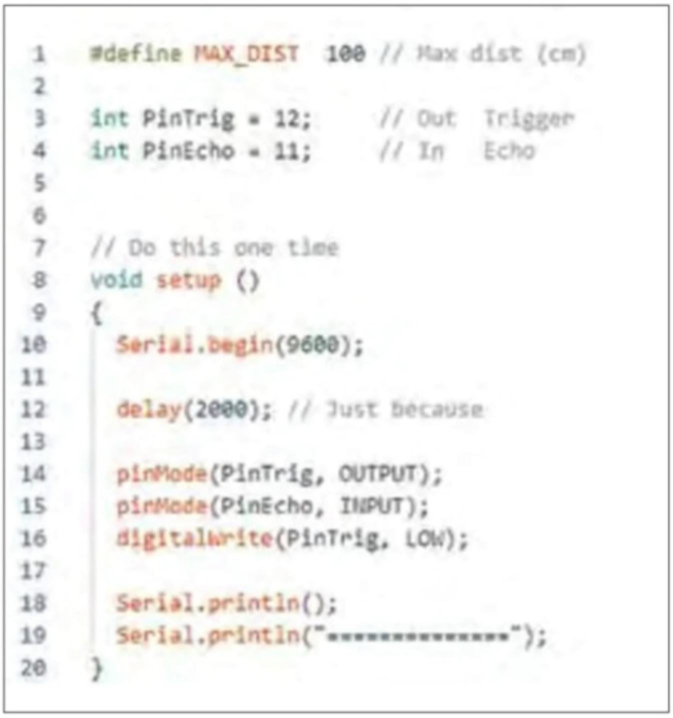


Fig.7. Adding the SR04 to the breadboard.



```
1   #define MAX_DIST  100 // Max dist (cm)
2
3   int PinTrig = 12;     // Out  Trigger
4   int PinEcho = 11;     // In   Echo
5
6
7   // Do this one time
8   void setup ()
9   {
10    Serial.begin(9600);
11
12    delay(2000); // Just because
13
14    pinMode(PinTrig, OUTPUT);
15    pinMode(PinEcho, INPUT);
16    digitalWrite(PinTrig, LOW);
17
18    Serial.println();
19    Serial.println("===============");
20  }
```

Listing 2a. Setting-up the SR04.

trimpot and light-dependent resistor (LDR) along with any of *their* ancillary wires and components.

Next, we are going to add one or both of the original GND wires back to our 7-segment display (Fig.6). As you may recall, we removed these wires in our previous column (*PE*, January 2024) in order to add the transistor, which we used to control the brightness of the display.

Since these wires connect to pins 3 and 8 of the display, and since they are connected inside the device, we really need only one of the wires. The reason for adding both is (a) we can and (b) to 'play safe.'

Now it's time to add our SR04 ultrasonic sensor to the breadboard. Observe that I've bent its pins back to make it point upwards from the breadboard (Fig.7).

Just to ensure we're all tap-dancing to the same skirl of the bagpipes, you can download an image of our entire current breadboard layout showing the SR04, piezoelectric buzzer and 7-segment display – along with any ancillary components – coupled with the connections to our Arduino Uno (file **CB-Feb24-01.pdf**). As usual, all the files mentioned in this column are available from the February 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

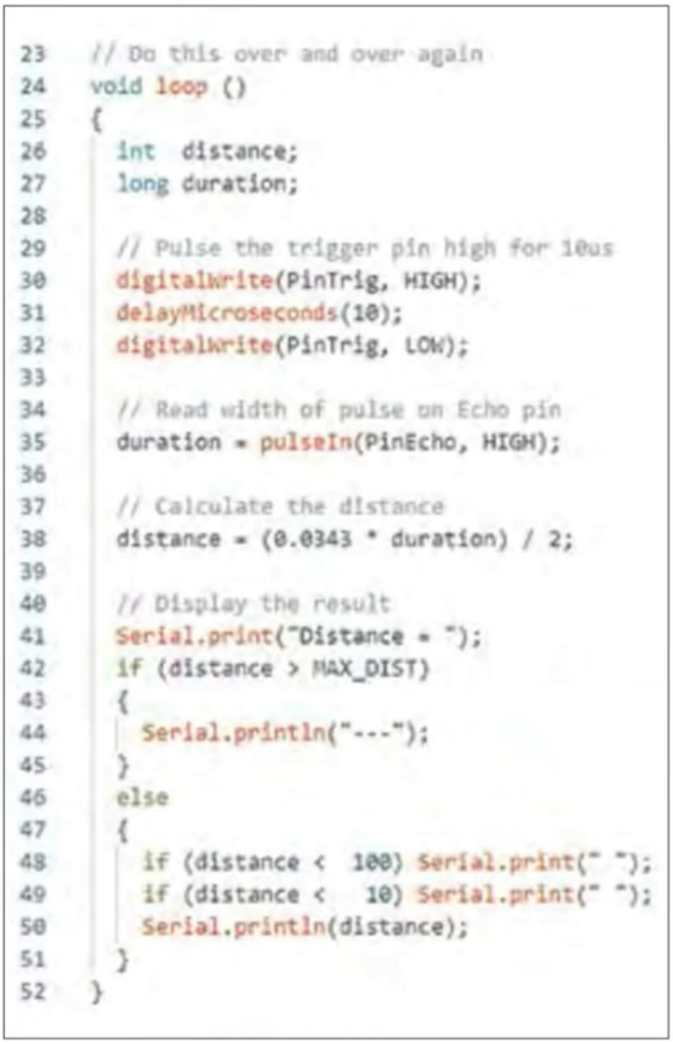
Are you ready to power-up this little beauty? Me too!

Ping… ping… ping…

The thought of a submarine just popped into my head accompanied by the 'ping… ping… ping…' sound of its sonar, which stands for 'sound navigation ranging.' More generally, according to Wikipedia, 'Sonar is a technique that uses sound propagation to navigate, measure distances, and communicate with or detect objects on or under the surface of the water.' When you think about it, we are doing something similar in air by implementing a form of acoustic radar, or 'sodar', which stands for 'sonic detection and ranging.'

As usual, we are going to take things step by step. We will commence by ensuring that our ultrasonic sensor is functioning as we expect. We've already wired everything up, so now it's time to turn our attention to the software. We will start with a simple program file: **CB-Feb24-02.txt**

Since our first program is so small, it's worth considering it in its entirety. We'll start by setting everything up as shown in Listing 2a. (Remember that, following some confusion in earlier columns, we're now using a scheme in which the listing number [Listing 2 in this example] corresponds to the associated program file (**CB-Feb24-02.txt** in this example), after which we use 'a', 'b', 'c' … suffixes as appropriate.)



```
23  // Do this over and over again
24  void loop ()
25  {
26    int  distance;
27    long duration;
28
29    // Pulse the trigger pin high for 10us
30    digitalWrite(PinTrig, HIGH);
31    delayMicroseconds(10);
32    digitalWrite(PinTrig, LOW);
33
34    // Read width of pulse on Echo pin
35    duration = pulseIn(PinEcho, HIGH);
36
37    // Calculate the distance
38    distance = (0.0343 * duration) / 2;
39
40    // Display the result
41    Serial.print("Distance = ");
42    if (distance > MAX_DIST)
43    {
44      Serial.println("---");
45    }
46    else
47    {
48      if (distance <  100) Serial.print(" ");
49      if (distance <   10) Serial.print(" ");
50      Serial.println(distance);
51    }
52  }
```

Listing 2b. Using the SR04.

I'm sitting at my desk with my breadboard in front of me and my SR04 pointing toward the ceiling. I'm planning on using the SR04 to measure the height of my hand above the sensor. Since I'm lazy and have no intention of standing up, on Line 1 I've defined `MAX_DIST` as being 100, which is the maximum distance I'm interested in measuring specified in centimeters.

On Lines 3 and 4 we declare two integers, `PinTrig` and `PinEcho`, to which we assign the numbers of the Arduino pins we've connected to the SR04's `TRIG` and `ECHO` terminals, respectively. Next, in the `setup()` function, we initialise our serial communications (Line 10), define the modes for our pins (Lines 14 and 15), tell the `PinTrig` pin to output a `LOW` (logic 0) value (Line 16), and write a few lines of text to the Serial Monitor (Lines 18 and 19).

The `loop()` function, which is shown in Listing 2b, is where things start to get interesting. We start by declaring two variables on Lines 26 and 27: an `int` (integer) called `distance` and a `long int` (long integer) called duration. We use a `long int` for `duration` because this data type can store larger values than a regular `int` (we introduced the concepts of `int`, `short int` and `long int` in *PE*, September 2023).

On Lines 30, 31 and 32 we output a 10µs positive-going pulse on `PinTrig` to kick everything off. On Line 35 we use the Arduino's built-in `pulseIn()` function to read the width of the pulse generated by the SR04 on its `ECHO` pin, which we've connected to `PinEcho` on the Arduino. On Line 38 we use the equation we discussed in excruciating detail earlier to calculate the distance to any object in centimeters. Finally, on lines 41 through 51 we display the result on the Serial Monitor, after which we return to the start of the `loop()` function and do it all again.

When you first run this program and open the Serial Monitor on your host computer, you should see the following:

```
==============
Distance = ---
Distance = ---
Distance = ---
          :
```

If you now place your hand in the air over the sensor and move it up and down, you'll start to see values like the following:

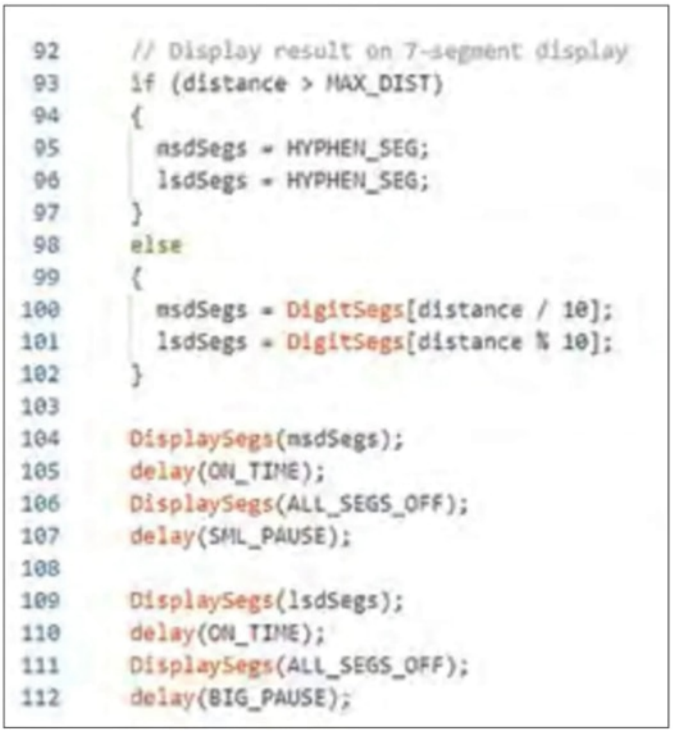
```
Distance = ---
Distance = ---
Distance =  23
Distance =  24
Distance =  23
Distance =  22
    :
```

If you see only 0 values, check that you've got the wires linking the SR04 to the Arduino plugged into the correct locations at each end and that you've used the right pin numbers in your code (no, of course I'm not speaking from experience – why would you ask?).

I've said it before, and I'll doubtless say it again – even though this is all simple stuff in the grand scheme of things, I still get a real thrill when (a) I implement the hardware and software to do something like use an ultrasonic sensor to detect and report the motions of my hand waving in the air and (b) everything actually works as planned!

Adding the 7-segment display

We are currently in the enviable position that we are no longer obliged to create everything from scratch. Instead, we can use bits and pieces of our previous programs like LEGO building blocks to create new implementations. That's what I've just done. I took the code we just created and merged it with an earlier program that wrote the decimal digits 0 through 9 to the display. I invite you to feast your orbs on the result (file **CB-Feb24-03.txt**).



```
 92   // Display result on 7-segment display
 93   if (distance > MAX_DIST)
 94   {
 95     msdSegs = HYPHEN_SEG;
 96     lsdSegs = HYPHEN_SEG;
 97   }
 98   else
 99   {
100     msdSegs = DigitSegs[distance / 10];
101     lsdSegs = DigitSegs[distance % 10];
102   }
103
104   DisplaySegs(msdSegs);
105   delay(ON_TIME);
106   DisplaySegs(ALL_SEGS_OFF);
107   delay(SML_PAUSE);
108
109   DisplaySegs(lsdSegs);
110   delay(ON_TIME);
111   DisplaySegs(ALL_SEGS_OFF);
112   delay(BIG_PAUSE);
```

Listing 3a. Displaying 2-digit distance on the 7-segment display.

We won't go through the entire program here, but there are a few points worth noting. For example, we've reduced `MAX_DIST` (the maximum distance we wish to measure) from 100cm to 99cm because we wish (it's easier) to display only two digits that can range between 00 and 99.

Hmmm. Two digits. The problem is that we currently have only one 7-segment display. Of course, one way around this would be to add more 7-segment displays, which is what we will be doing in future columns. The alternative is to use our single display to present both digits.

If we call our most-significant and least-significant digits MSD and LSD, respectively, and if we think of '…' as indicating a pause, then a first-pass view would be to display MSD … LSD … … … MSD … LSD … … …, and so forth.

We've also got to consider the case where the distance read from the SR04 is greater than 99. In our previous program, we simply wrote hyphen ('-') characters to the Serial Monitor. We are going to do the same thing with our 7-segment display, which is why we've defined `HYPHEN_SEG` as being `B00000010`, where the '1' equates to the horizontal 'G' segment in the middle of the display.

Three more new definitions are as follows: `ON_TIME` (initially set to 200ms), which is the time a digit will be displayed; `SML_PAUSE` ('small pause,' initially set to 100ms), which is the time we will turn the display off between the digits forming a pair; and `BIG_PAUSE` (initially set to 700ms), which is the time we will turn the display off between pairs of digits.

Most of the program will be familiar from our previous experiments. The only new part is where we take the distance read from the SR04 and present it on the 7-segment display as illustrated in Listing 3a.

At the start of our `loop()` function (not shown here), we've declared two variables of type `byte` that we've called `msdSegs` and `lsdSegs`. We will use these variables to hold the segments associated with the MSD and LSD, respectively.

On Line 93 we perform a test to see if the distance measured by the SR04 is greater than 99cm. If so, on Lines 95 and 96, we assign the bit pattern associated with our hyphen segment to both `msdSegs` and `lsdSegs`. Otherwise, on Lines 100 and 101, we assign the bit patterns associated with most- and least-significant digits to `msdSegs` and `lsdSegs`, respectively.

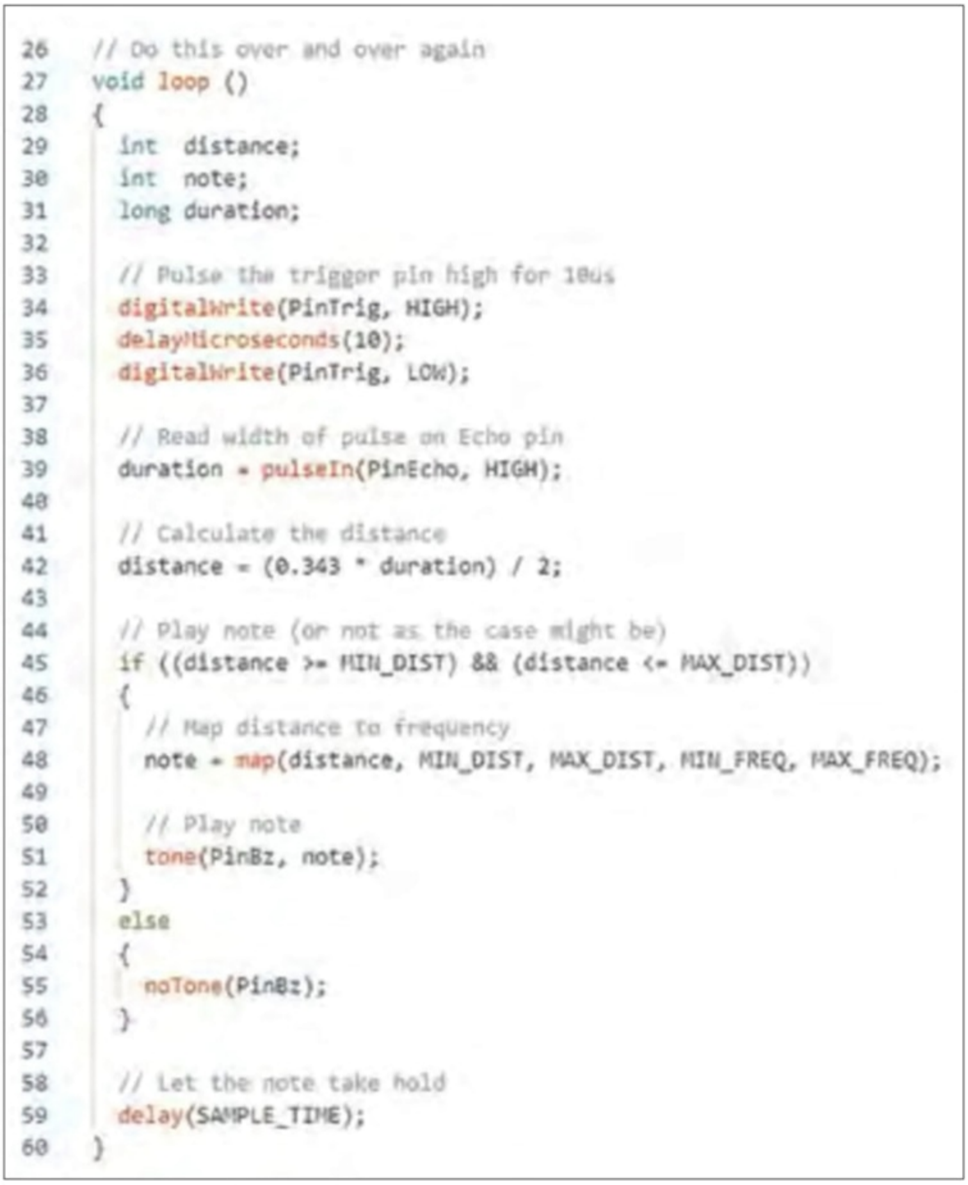
How does this work? Well, suppose our distance measurement is 42. Since we are working with integers, the division operation `42 / 10` will return a value of 4, which

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.



```
26  // Do this over and over again
27  void loop ()
28  {
29    int  distance;
30    int  note;
31    long duration;
32
33    // Pulse the trigger pin high for 10us
34    digitalWrite(PinTrig, HIGH);
35    delayMicroseconds(10);
36    digitalWrite(PinTrig, LOW);
37
38    // Read width of pulse on Echo pin
39    duration = pulseIn(PinEcho, HIGH);
40
41    // Calculate the distance
42    distance = (0.343 * duration) / 2;
43
44    // Play note (or not as the case might be)
45    if ((distance >= MIN_DIST) && (distance <= MAX_DIST))
46    {
47      // Map distance to frequency
48      note = map(distance, MIN_DIST, MAX_DIST, MIN_FREQ, MAX_FREQ);
49
50      // Play note
51      tone(PinBz, note);
52    }
53    else
54    {
55      noTone(PinBz);
56    }
57
58    // Let the note take hold
59    delay(SAMPLE_TIME);
60  }
```

Listing 4a. The heart of the therebone.

is our most-significant digit, while the modulus operation `42 % 10` will return a value of 2 (the remainder from the division), which is our least-significant digit.

Lines 104 through 107 display the most-significant digit for a duration of `ON_TIME` followed by a short blanking period with a duration of `SML_PAUSE`. Lines 109 through 112 display the least-significant digit for a duration of `ON_TIME` followed by a longer blanking period with a duration of `BIG_PAUSE`.

I can't stop myself from chortling as I move my hand up and down and see the result presented on both the Serial Monitor and on my 7-segment display. Even my wife (Gina the Gorgeous) was impressed, and that's not something I expect to hear myself say very often!

Sound the therebone!

As we've previously discussed, an unexpected entry to the weird and wonderful musical instruments of the 20th Century was the theremin (**https://bit.ly/3ubLrBj**). This eldritch-sounding gizmo was named after its inventor, the Russian physicist Lev Sergeyevich Termen, who is known in the West as Leon Theremin. Invented in 1919 and patented in 1928, the theremin was the product of Soviet government-sponsored research into proximity sensors.

Now, by (total lack of) popular request, we dare to present our 21st Century rebuttal instrument in the form of the soon-to-be-legendary therebone™, whose moniker is derived from the fact that I used to play the trombone in the Sheffield Schools Orchestra deep in the mists of time.

I just forked our previous program to create a new version in which we use the distance measured using our ultrasonic range finder to control the frequency of notes played on our piezoelectric buzzer, file **CB-Feb24-04.txt**.

In our previous program, we decided to measure distance in units of centimeters. In the case of our new program, I've decided to use units of millimeters. Assuming the speed of sound to be 343m/s, this equates to 343,000mm/s. And, since we're measuring time in units of µs, this equates to 0.343mm/µs, which is the value we will use in our equation.

We start with four definitions: `MIN_DIST` ('minimum distance,' which we set to 20mm), `MAX_DIST` ('maximum distance,' which we set to 999mm), `MIN_FREQ` ('minimum frequency,' which we set to 31Hz), and `MAX_FREQ` ('maximum frequency,' which we set to 4,978Hz).

The 31Hz and 4,978Hz values correspond to B0 and DS8 in scientific pitch notation (SPN), also known as American standard pitch notation (ASPN) and international pitch notation (IPN).

We also define a `SAMPLE_TIME` as being 40ms. I'll explain why we need this in a moment. We use only three of the Arduino's pins in this program: pin 12 (`PinTrig`) and pin 11 (`PinEcho`) for the SR04, and pin 10 (`PinBz`) to drive our piezo buzzer.

Most of the program is self-explanatory, but it's worth our while to consider the contents of the `loop()` function, as illustrated in Listing 4a.

The first point to note is Line 42, where we use our new value of 0.343mm/µs to calculate distance in millimeters.

Remembering that we are going to use our hand to control the frequency of a musical note, one point to consider is what we are going to do if our hand moves outside the permitted range. Initially, I was toying with the idea of using the Arduino's built-in `constrain()` function to constrain our distance value to always fall between `MIN_DIST` and `MAX_DIST`. The way I would have done this would be to add the following statement to Line 43:

```
distance = constrain(distance, MIN_DIST, MAX_DIST);
```

A more generic representation is as follows:

```
r = constrain(x, a, b);
```

This will return `x` if `x` is between `a` and `b`; it will return `a` if `x` is less than `a`; and it will return `b` if `x` is greater than `b`.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

But then I realised that, if I wasn't careful, removing my hand from being in front of the SR04 would leave the current note playing ad infinitum. So, instead of using the `constrain()` function, I added the `if()` test on Line 45. If the measured distance falls in the allowable range, then we call the Arduino's `map()` function on Line 48 to map the distance in mm to a corresponding frequency in Hz (we introduced this function in *PE*, October 2023), after which we call the `tone()` function on Line 51 to play the desired note (we introduced this function in *PE*, December 2023). As soon as the measured distance falls outside the allowable range – such as when I remove my hand from being in front of the SR04 – then we call the `noTone()` function on Line 55 to turn off the currently playing note.

When I ran the first iteration of this program, the sound was ~~horrible~~ indescribable. I quickly realised that I was repeatedly calling the `tone()` function so quickly that it didn't have time to actually do anything worth doing. This is why I added the delay on Line 59, after which the sound was… everything we might expect.

All joking aside, this actually sounds pretty good considering the parts and techniques we are using. The quality of the sound could be dramatically improved by replacing the piezo buzzer with a regular loudspeaker and by adding some analogue signal processing (ASP) circuitry. All-in-all, however, I'm very pleased with the result.

A theremin has two controls – one for pitch and one for volume. Based on this, one future therebone enhancement might be to add a second SR04, thereby allowing the therebone artist to control the pitch with one hand and the volume with another.

Although my dad was English, he was a member of the 15th Scottish Reconnaissance Regiment during WWII. Dad told me that the regimental pipers played their great Highland bagpipes through the night before the company went into battle. The idea was to plant fear, uncertainty, and doubt (FUD) into the minds of the enemy. Dad said that he didn't know what effect it had on the Germans, but after a night of listening to the bagpipes, he was prepared to fight anyone. We can only wonder what he would have thought about the therebone.

Components from Part 1	
LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Solderless breadboard	https://amzn.to/3O2L3e8
Multicore jumper wires (male-male)	https://amzn.to/3O4hnxk
Components from Part 2	
7-segment display(s)	https://amzn.to/3Afm8yu
Components from Part 5	
Momentary pushbutton switches	https://amzn.to/3Tk7Q87
Components from Part 6	
Passive piezoelectric buzzer	https://amzn.to/3KmxjcX
Components for Part 9	
SW-18010P vibration switch	https://bit.ly/46SfDA4
Components for Part 10	
Breadboard mounting trimpots	https://bit.ly/3QAuz04
Components for Part 12	
Light-Dependent Resistor	https://bit.ly/3S2430m
Components for Part 13	
BC337 NPN Transistor	https://bit.ly/40xAgyS
Components for Part 14	
HC-SR04 Ultrasonic Sensor	https://bit.ly/49AMBq4

Broken promises

In my previous column, I said that one of the things we were going to do in this column was introduce the concept of real-time clocks (RTCs). Paradoxically, we don't have enough time, so we will have to punt those discussions to our next column. Until then, as always, have a good one!

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Circuit Surgery

Regular clinic by Ian Bell

Frequency shifting and superheterodyne receivers – Part 3

In the last two issue we have been looking at superheterodyne radio receivers. We started with the principles of heterodyning (frequency shifting) and the mixers that provide this function. Last month, we discussed the structure and operation of superheterodyne radio receivers in more detail, up to the intermediate frequency stage. This month, we look at demodulation.

Recap of superhet operation

The principle of the superheterodyne receiver is based on frequency shifting (heterodyning) to a fixed intermediate frequency (IF) before further shifting to the baseband to recover the message signal. The fact that the IF is a fixed frequency makes the design of a receiver easier than if most of the circuitry has to cope with (be tuneable to) the full range of carrier frequencies which need to be received. Heterodyning is achieved using mixers. These are nonlinear circuits (ideally multipliers) that combine signals to produce new frequencies (heterodynes) not present in the input. With two input frequencies (two sinusoidal inputs) multipliers output just the sum and difference frequencies, whereas with other nonlinear circuits there may be many other output frequencies.

Fig.1 shows the structure of a superheterodyne receiver to the IF stage. The mixer combines the received signal (carrier frequency, f_c) with the local oscillator frequency (f_{LO}), which may be at a higher (high-side injection) or lower (low-side injection) frequency than the carrier. With a high-side local oscillator, the mixer produces signals at ($f_{LO} - f_c$) and ($f_{LO} + f_c$), with their sidebands (message bandwidth). We only need to use one of these signals as the IF signal for further processing (eg, $f_{IF} = f_{LO} - f_c$) so the other is removed by the IF filter. The IF filter also removes frequencies resulting from the presence of other radio stations/channels and those due to non-ideal behaviour of the mixer. The receiver is tuned by the local oscillator frequency and the majority of unwanted signals are removed by the IF filter. The IF is at fixed frequency, so it is easy to create a filter with high performance at low cost.

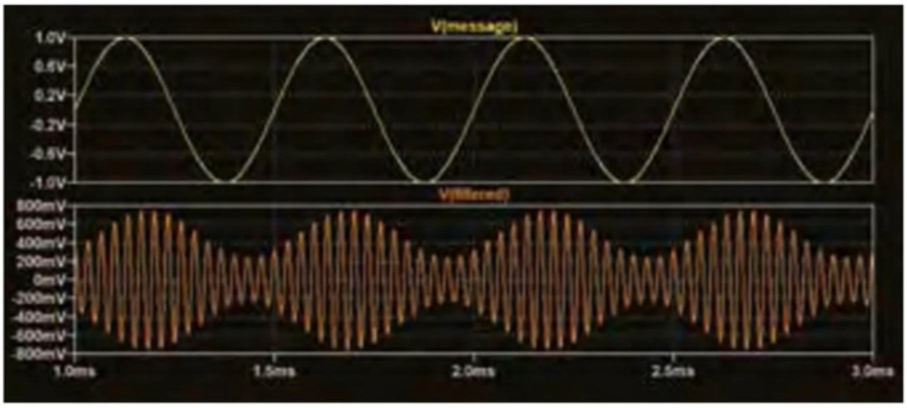


Fig.2. Waveform of filtered IF mixer output from the receiver in Fig.1.

There is one unwanted signal which the IF filter cannot remove – this is called the image frequency and is due to the second received frequency (station/channel) that the mixer will shift to f_{IF}. For example, if we want $f_{IF} = f_{LO} - f_c$ then the image frequency f_{Im}, where $f_{Im} = f_c + f_{LO}$ will also be shifted to f_{IF} by the mixer. As this is at the same frequency as the wanted signal it cannot be removed after the mixer. This requires a filter before the mixer, called the image filter or preselection filter, which may be tuneable to track with the local oscillator. However, the requirements for this filter are a lot less severe than if we tried to filter the required station/channel directly from the RF signal received from the antenna.

Demodulation

The process of recovering the message signal from the IF signal is called demodulation or detection. There are a range of modulation techniques – one or more of the carrier's amplitude, frequency and phase can be modulated, and the demodulation used must be appropriate for the received signal. To keep things simple, we are only considering amplitude modulation (AM) here. Using AM and with a sinusoidal message signal the IF signal looks like the lower waveform in Fig.2. The upper waveform is the message that we need to recover. These waveforms are from the simulations discussed last month. As previously noted, the frequencies and

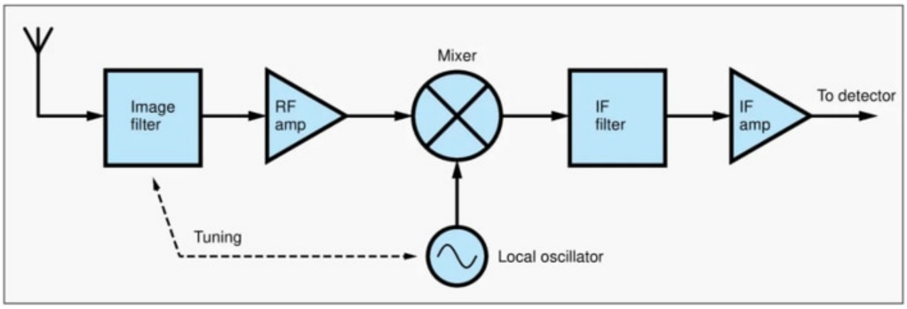


Fig.1. Superheterodyne receiver structure.

Introduction to LTspice

Want to learn the basics of LTspice? Ian Bell wrote an excellent series of *Circuit Surgery* articles to get you up and running, see *PE* October 2018 to January 2019, and July/August 2020. All issues are available in print and PDF from the *PE* website: **https://bit.ly/pe-backissues**

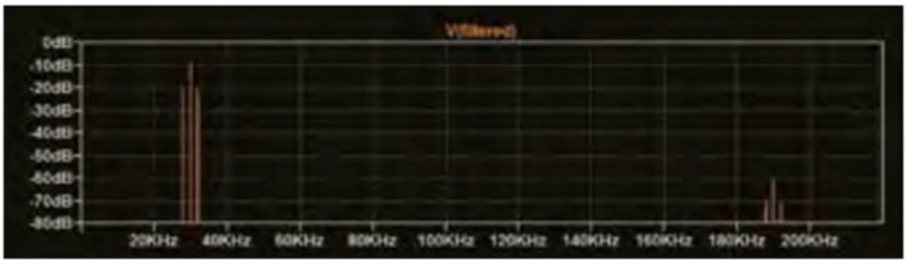


Fig.3. Spectrum of filtered IF waveform from the receiver in Fig.1.

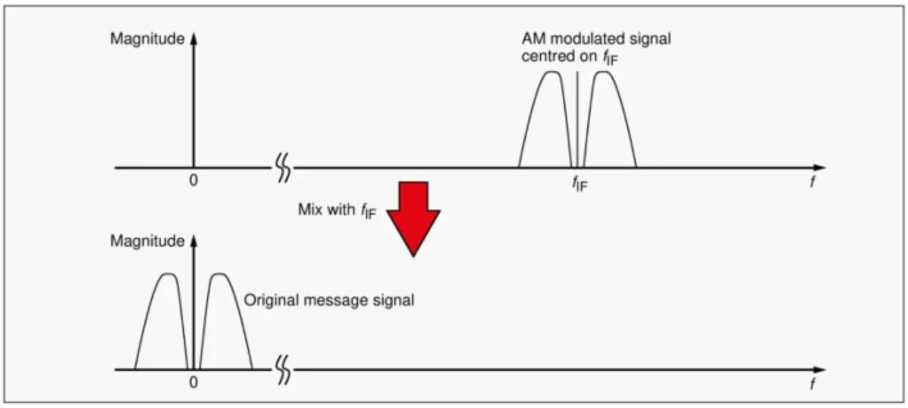


Fig.4. Downshifting to DC can be used to demodulate an AM signal.

relative frequencies used in our examples are chosen to make the waveforms easy to view and are not representative of typical radio signals.

As discussed previously when discussing radio systems, it is common to look at the spectra (amplitude vs frequency plots) of the signals of interest. The spectrum of the IF signal from Fig.2 is shown in Fig.3.

Looking at Fig.2 and Fig.3 we can see possible ways to recover the message signal. In Fig.2 we can see that if we 'joint the dots' of the signal peaks we obtain a sinusoidal at the message frequency. We can recover the message from an AM signal by following the amplitude envelope of the waveform – this is known as envelope detection, which we will look at in more detail shortly.

Alternatively, looking at the spectrum, we could mix the received IF signal (at f_{IF}) with an oscillator output at f_{IF}. This will produce sum and difference frequencies of ($f_{IF} - f_{IF} = 0$; ie, DC) and ($f_{IF} + f_{IF} = 2f_{IF}$). The $2f_{IF}$ (and other unwanted frequencies) can be removed using a low-pass filter leaving the signal that is shifted to DC, which is the original message. This is illustrated in Fig.4. We will look at demodulation using this approach later.

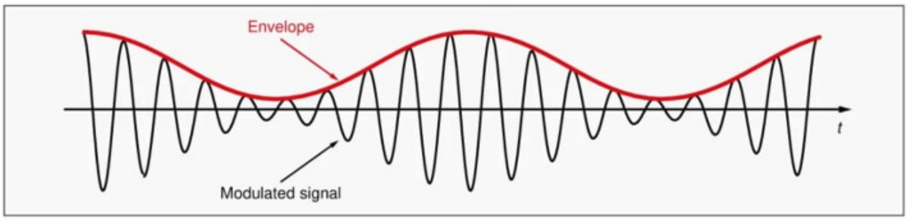
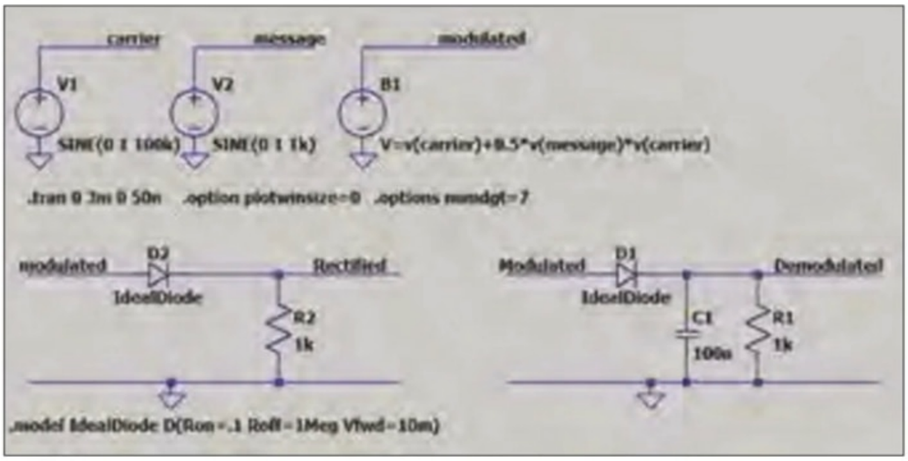


Fig.5. Amplitude-modulated signal and its envelope.



```
SINE(0 1 100k)
SINE(0 1 1k)
V=v(carrier)+0.5*v(message)*v(carrier)
.tran 0 3m 0 50n
.option plotwinsize=0
.options numdgt=7
.model IdealDiode D(Ron=.1 Roff=1Meg Vfwd=10m)
```

Fig.7. LTspice schematic for investigating the envelope detector.

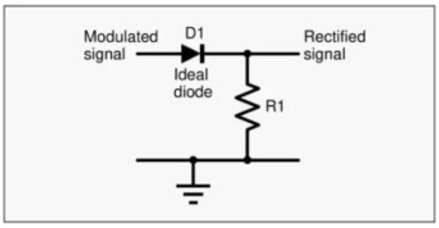


Fig.6. Rectifying an AM signal.

As discussed last month, the message is in the sidebands of the modulated signal, which are above and below the centre frequency. This implies that one of the sideband will have negative frequencies (see Fig.4), which may seem strange. In fact, negative frequencies are a consequence of the mathematics of frequency domain representation of signals (Fourier transform) which is related to the use of complex numbers to represent signals and the need to consider both amplitude and phase. A sinusoidal wave has equal-amplitude positive and negative frequencies when plotted as a spectrum which includes negative frequencies.

Envelope demodulator

An envelope demodulator (or envelope detector) outputs a signal which tracks the peaks of a waveform, as shown in Fig.5. It should be clear that this only works if just the positive or negative peaks are tracked (Fig.5 uses the positive peaks). This implies that the envelope detector circuit must rectify the signal. Usually, in basic receivers, this is half-wave rectification (see Fig.6) which removes the peaks of one polarity, but full-wave rectification could be used.

The circuit in Fig.6 shows a half wave rectifier using a single diode, which can form part of an envelope detector. The diode alone is not sufficient as the output does not track the envelope. The modulated signal must be larger in amplitude than the diode switch-on (forward) voltage, otherwise part of the signal will be lost. More specifically, with reference to Fig.5, the minimum envelope voltage must be greater than the forward voltage – however, for simplified simulations to illustrate principles of operation we can use an ideal diode (zero forward voltage).

Fig.7 shows an LTspice schematic which can be used for investigating the envelop detector. This includes the rectifier just mentioned, and the envelope detector which we will discuss shortly. The AM signal is generated using the approach that was discussed last month. The simulation results for the rectifier are shown in Fig.8. This uses different frequencies for the sources from those shown in Fig.7 (1kHz modulated onto 20kHz). The `.model` statement is used to define a close-to-ideal diode.

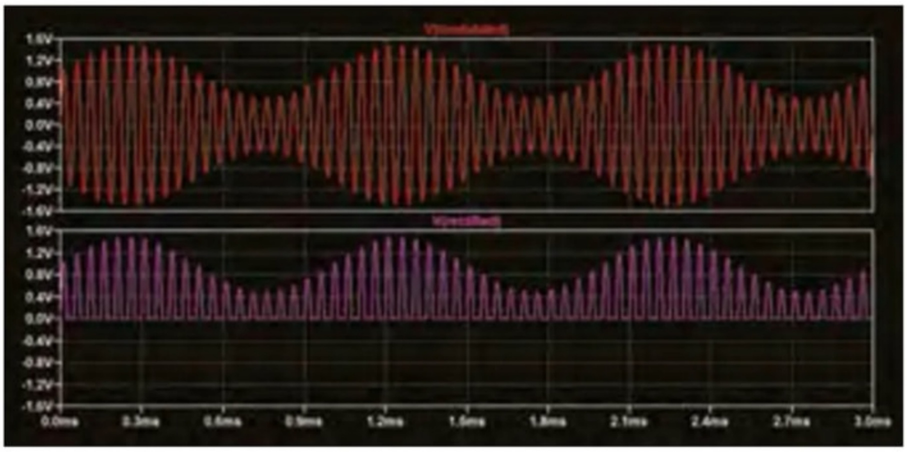


Fig.8. Simulation results for the rectifier from Fig.7 (using 1kHz modulated onto 20kHz).

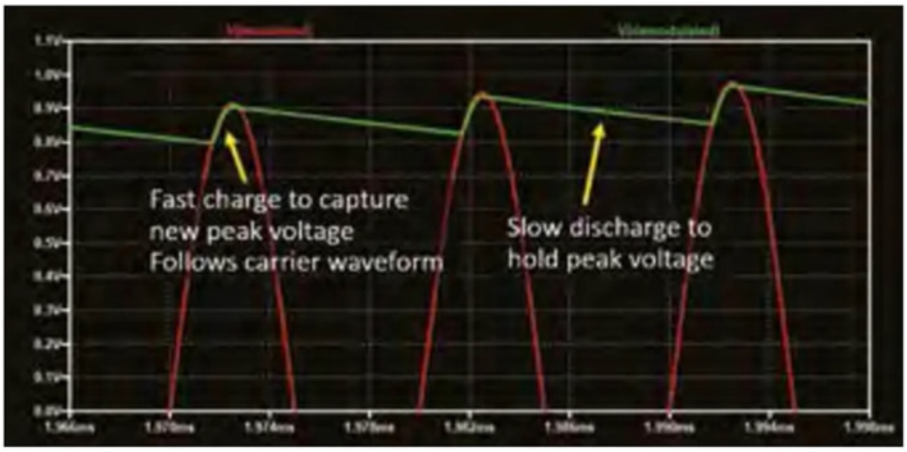


Fig.10. Peak detector operation (simulation results from Fig.7).

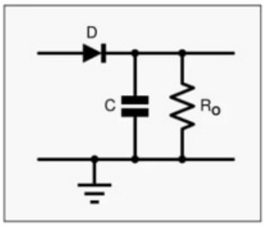


Fig.9. Envelope detector.

To track the envelope, it is necessary to hold the voltage of the rectified waveform peak until the next peak. This can be achieved with a capacitor – see Fig.9. The capacitor must charge quickly, following the carrier waveform to the peak voltage, but must discharge more slowly to hold the peak voltage sufficiently well until the next peak (see Fig.10).

The envelope detector has two states of operation depending on whether the diode is forward or reverse biased – we can draw two equivalent circuits, as shown in Fig.11. When the diode is forward biased the envelope detector behaves as the circuit shown on the bottom left of Fig.11, where R_D is the effective resistance of the diode. Assuming that R_D is much smaller than the output resistor R_O we can ignore R_O, and assume that the capacitor will charge to the input voltage via R_D. This leads to a charging time constant of $\tau_c = R_D C$.

An *RC* time constant (τ) is the time required to charge a capacitor through a resistor from zero to about 63% of the value of an applied DC voltage and provides a figure for the 'speed' of the circuit. In this case, we need the charge time to be much faster than one cycle time of the carrier cycle time ($1/f_c$) so that the voltage tracks the carrier (see Fig.10). This depends on the capacitor and effective diode resistance and should usually be straightforward to meet as long as the value of *C* is not very large.

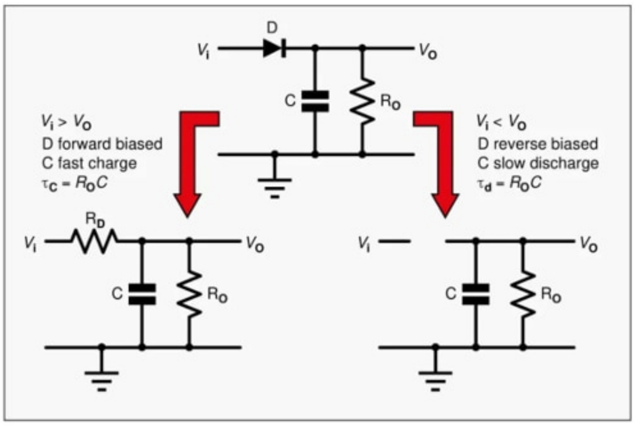


Fig.11. Equivalent circuits for envelope detector.

When the diode is reverse biased the envelope detector behaves as the circuit shown on the bottom right of Fig.11, where the diode is open circuit. The circuit will enter this state once the input voltage falls below the capacitor voltage (strictly speaking below the capacitor voltage plus diode forward voltage) as we pass a peak in the input waveform (see Fig.10). The capacitor will discharge through the output resistor with a discharge time constant of $\tau_d = R_O C$. The discharge time constant must be much longer than the carrier cycle time ($1/f_c$) but much shorter than the minimum message cycle time ($1/f_m$). Suitable choices of R_O and C should be able to achieve this.

Fig.12 to Fig.14 show waveforms for the envelope detector in Fig.7 with different time constants. The message frequency is 1kHz, which implies the discharge time constant must be much shorter than 1/1000 = 1ms. The carrier frequency is 100,000kHz, which implies the discharge time constant must be longer than 1/100000 = 10μs. A value between these, say τ_d = 100μs, is a suitable choice. If we use a 100nF capacitor, then an output resistor of $R_O = 1/\tau_d C$ = 1kΩ is suitable (as shown in Fig.7, where the output resistor is R1). Fig.12 shows the modulated and demodulated waveforms using these values. The envelope detector is working well. The ripple on the demodulated waveform can be removed using a low-pass filter to obtain a good copy of the original message signal. There is a DC offset which can be removed by AC coupling or high-pass filtering.

Fig.13 shows the modulated and demodulated waveforms with R1 changed to 10kΩ. The discharge time constant is too long. When the envelope is rising the circuit works well, holding the peak value nearly constant, but as the envelope falls the circuit is not able to discharge fast enough and loses track of the envelop. Fig.13 shows the modulated and demodulated waveforms with R1 changed to 100Ω. The discharge time constant is too short so that the output follows the carrier too much, producing a very large ripple amplitude.

An envelope detector can be used directly on the received radio signal, after a bandpass filter (or a set of tuned bandpass amplifiers to tune in the required station or channel). This approach was used in early receivers, and some radio ICs first developed in the 1970s, but has much lower performance than the superheterodyne approach because the whole system has to be tuned, and/or suffers reduced performance as the received frequency changes.

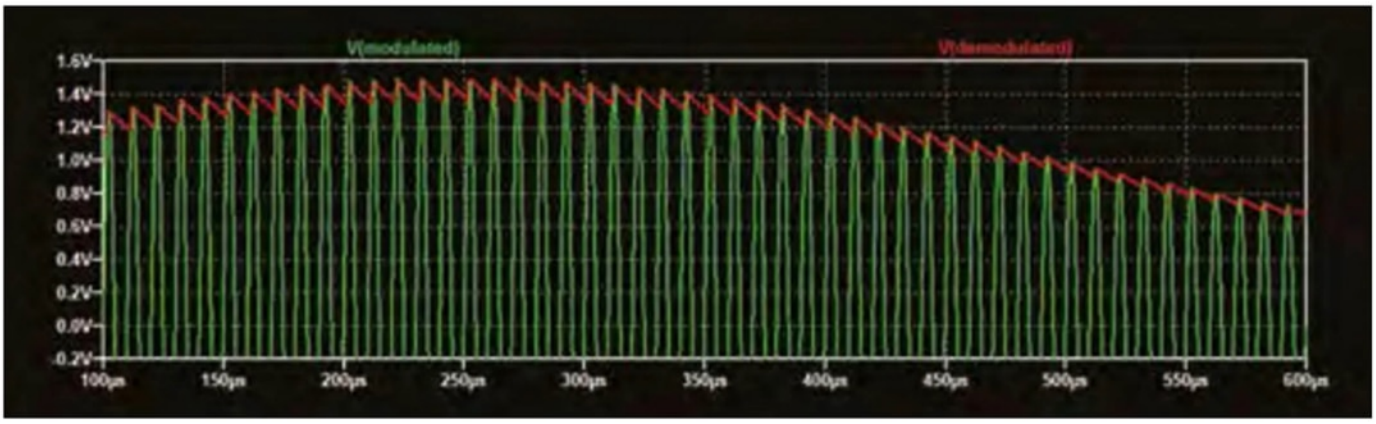


Fig.12. Waveforms for the envelope detector in Fig.7 with C1 = 100nF and R1 = 1kΩ.

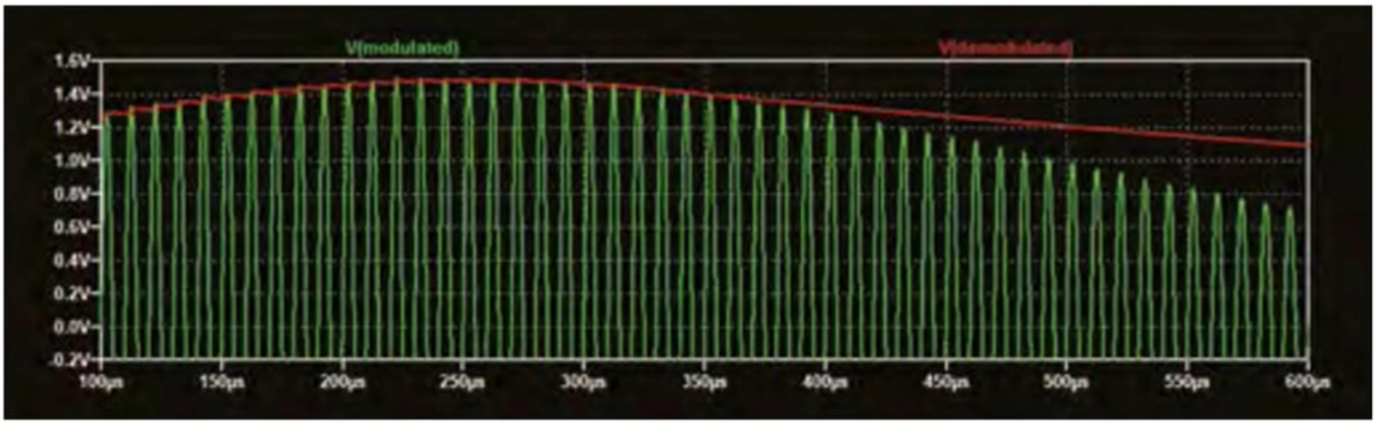


Fig.13. Waveforms for the envelope detector in Fig.7 with C1 = 100nF and R1 = 10kΩ.

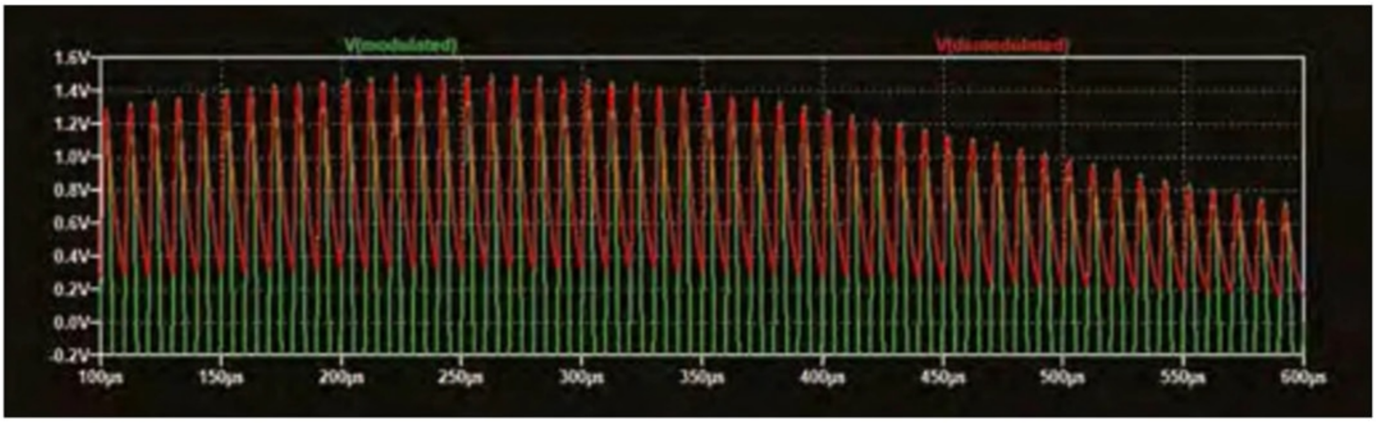


Fig.14. Waveforms for the envelope detector in Fig.7 with C1 = 100nF and R1 = 100Ω.

Using mixers for demodulation

As mentioned above, in theory we can demodulate AM by downconverting from the IF to baseband using a mixer. It is also possible to use a mixer to go straight from the received RF to baseband – this requires a local oscillator at exactly the same frequency as the carrier and is referred to as 'direct conversion receiver' (see Fig.15), it is also called a 'homodyne receiver'. This approach will work, but there are a number of difficulties and non-ideal behaviours which must be taken into account.

An LTspice simulation schematic for a direct conversion receiver is shown Fig.16. This has a structure very similar to the superhet circuit in Fig.8 last month; however, the local oscillator frequency is now equal to the carrier frequency, the filters are lowpass in baseband range (5kHz) because we are downconverting directly to baseband. We can also use a mixer to downconvert the IF to baseband in a superhet, in which case an oscillator at the IF is required. The direct conversion receiver has fewer blocks so is simpler to use.

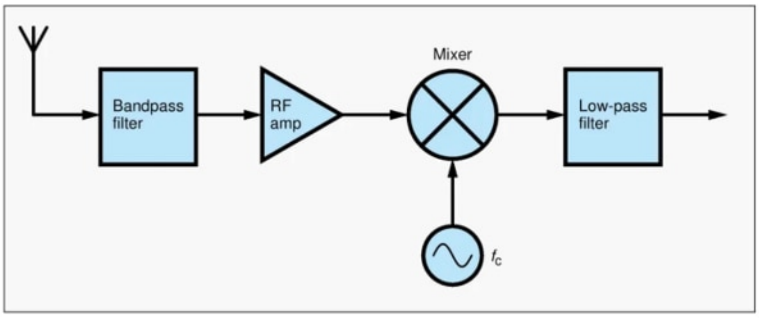


Fig.15. Direct conversion receiver.

A difficulty with using a mixer to demodulate AM is that the phase difference between the carrier and local oscillator affects the amplitude of the demodulated signal; for this reason the carrier and local oscillator sources have the phase specified on

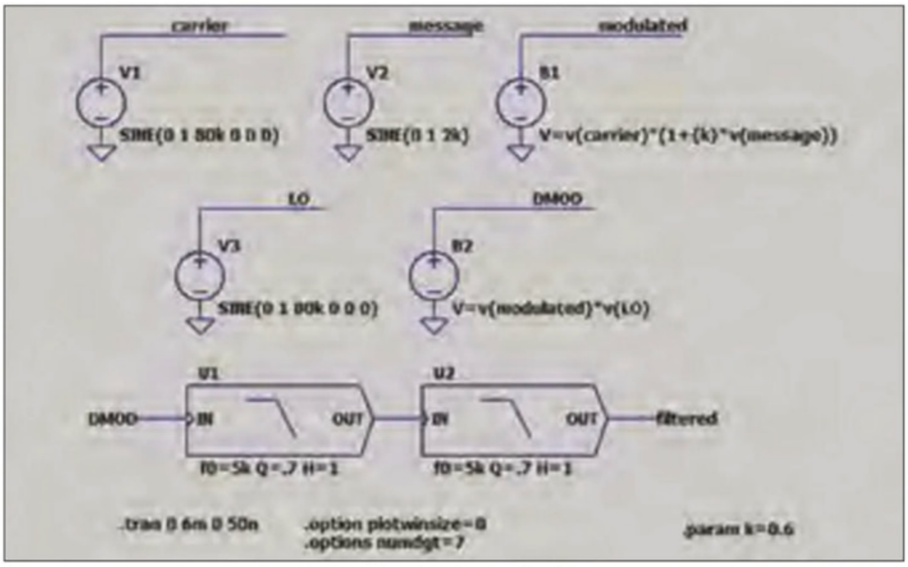


Fig.16. LTspice simulation schematic for a simple direct conversion receiver.

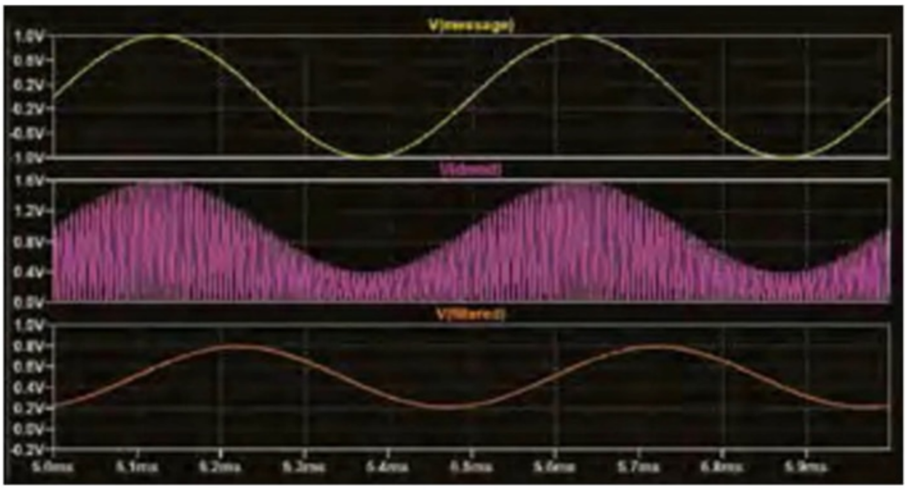


Fig.18. Simulation results from the circuit in Fig.16 with 0° phase difference between carrier and local oscillator.

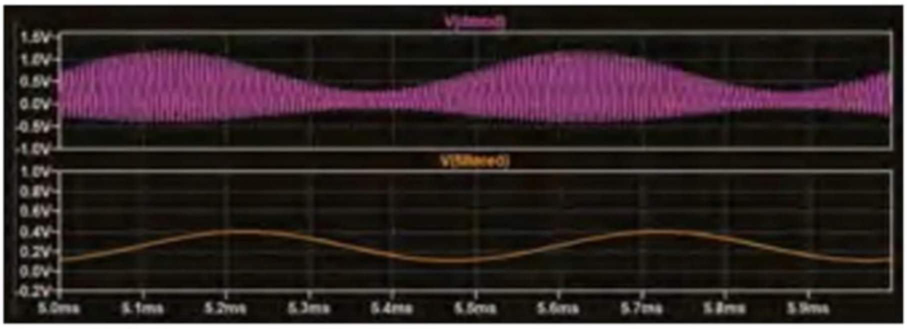


Fig.19. Simulation results from the circuit in Fig.16 with 60° phase difference between carrier and local oscillator.

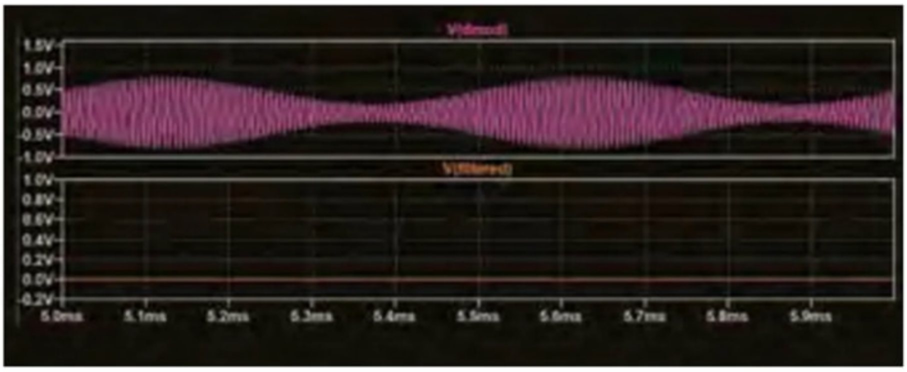


Fig.20. Simulation results from the circuit in Fig.16 with 90° phase difference between carrier and local oscillator.

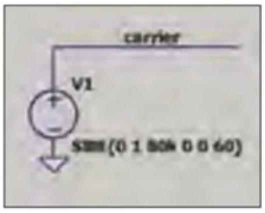


Fig.17. Carrier source from Fig.16 with phase set to 60°.

the schematic in Fig.16. The phase of a sinusoidal source can be set in LTspice by right clicking on the source symbol and entering the value (in degrees) in the `Phi(deg)` box of the source settings dialog. Fig.17 shows the carrier source phase set to 60°. Fig.18 to Fig.20 show the mixer output (demod) and filtered baseband signal for 0°, 60°and 90° phase difference between the transmitted carrier and local oscillator. At 60° the amplitude is diminished and at 90° the demodulated output is zero. Additional mechanisms are required to ensure the correct phase difference is maintained if this approach is used.

Quadrature demodulation

A solution to the phase difference problem is to use what is known as a quadrature demodulator. This uses two mixers fed with signals 90° out of phase (see Fig.21). The term quadrature comes from 'quarter' because 90° is a quarter of a complete rotation of 360°. The output of the mixers (after filtering to remove unwanted frequencies) are referred to as the in-phase (*I*) and quadrature (*Q*) signals. Quadrature demodulators are also referred to a *I*/*Q* demodulators.

The *I* and *Q* signals can be combined to obtain a constant amplitude demodulated output by calculating $\sqrt{(I^2+Q^2)}$ (they cannot simply be added because of the 90° phase difference). This could be done using analogue circuitry but is typically performed using digital signal processing (DSP). Although it is not required for simple AM demodulation, the *I* and *Q* signals can also be used to calculate phase, which can be used with phase or combined phase/amplitude modulation.

Connecting the circuit in Fig.21 to the output of the superhet receiver in Fig.1 creates a 'dual conversion receiver' which requires two low-frequency (baseband) analogue-to-digital converters (ADCs) to digitise the *I* and *Q* signals for further processing. However, the DSP is not limited to the baseband and the functionality shown in Fig.21 can be implemented digitally with the IF digitised using a single high-speed ADC.

Fig.22 shows an LTspice schematic based on Fig.22. Sources `V3` and `V4` generate the two local oscillator signals with 90° phase difference. The demodulated output is calculated

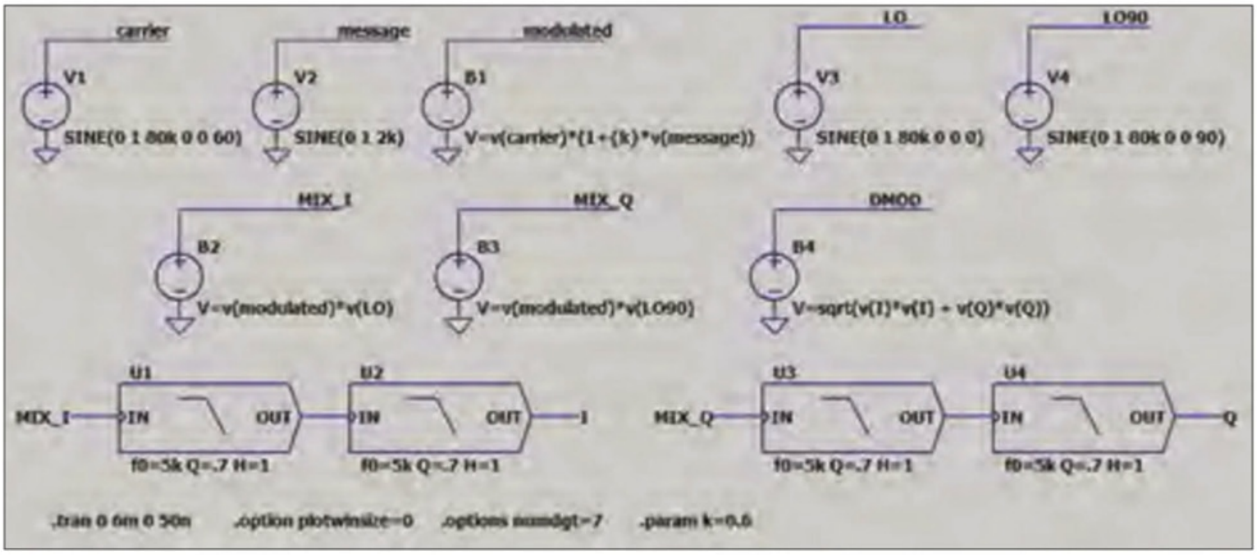

carrier
message
modulated
LO
LO90
V1
SINE(0 1 80k 0 0 60)
V2
SINE(0 1 2k)
B1
V=v(carrier)*(1+{k}*v(message))
V3
SINE(0 1 80k 0 0 0)
V4
SINE(0 1 80k 0 0 90)
MIX_I
B2
V=v(modulated)*v(LO)
MIX_Q
B3
V=v(modulated)*v(LO90)
DMOD
B4
V=sqrt(v(I)*v(I) + v(Q)*v(Q))
U1
U2
U3
U4
MIX_I
IN
OUT
f0=5k Q=.7 H=1
I
MIX_Q
Q
.tran 0 6m 0 50n
.option plotwinsize=0
.options numdgt=7
.param k=0.6

Fig.22. LTspice simulation schematic for a quadrature decoder for AM.

using behavioural source `B4` with `V=sqrt(v(I)*v(I) + v(Q)*v(Q))`. Other parts of the schematic are similar to previous examples.

Fig.23 to Fig.25 show the Q and I and demodulated signals for 0°, 60° and 90° phase difference between the transmitted carrier and local oscillator.

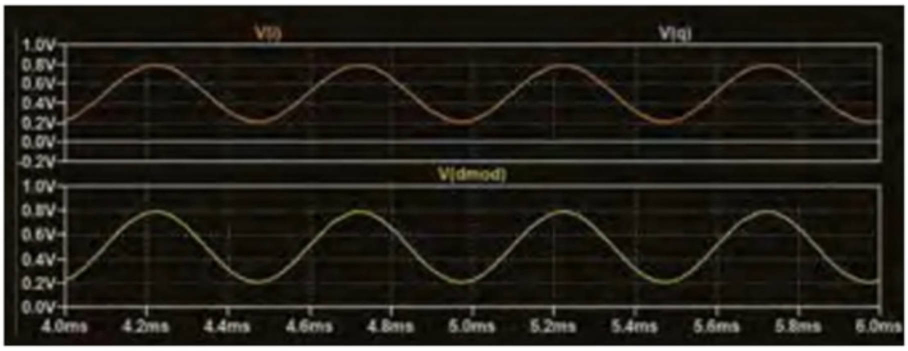


Fig.23. Simulation results from the circuit in Fig.22 with 0° phase difference between carrier and local oscillator.

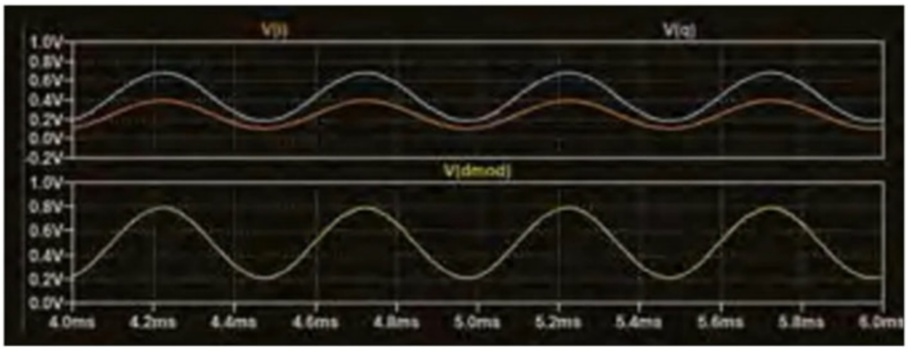


Fig.24. Simulation results from the circuit in Fig.22 with 60° phase difference between carrier and local oscillator.

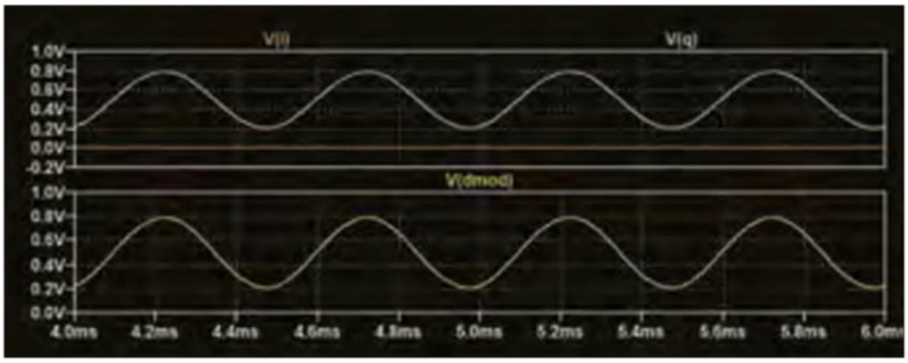


Fig.25. Simulation results from the circuit in Fig.22 with 90° phase difference between carrier and local oscillator.

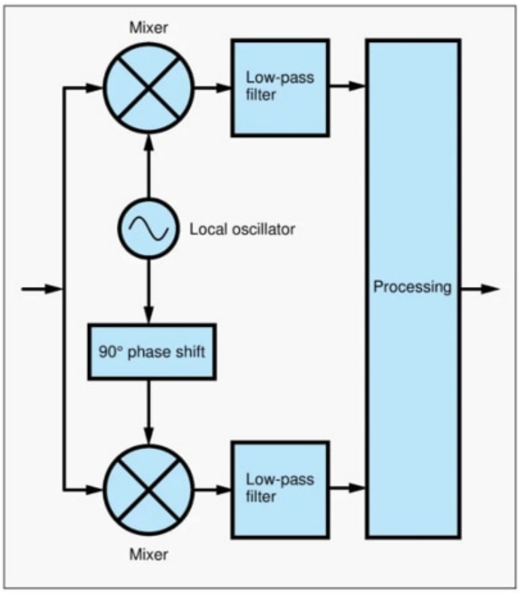

Mixer
Low-pass filter
Local oscillator
Processing
90° phase shift
Low-pass filter
Mixer

Fig.21. Basic quadrature demodulator.

The I and Q signal amplitudes vary as phase difference changes, but the final demodulated output is constant.

Quadrature techniques are widely used in radio systems and are not restricted to AM demodulation. Two inputs (I and Q) can be used to modulate both the amplitude and phase of a carrier at the transmitter, referred to as 'QAM'. The quadrature demodulator can recover both phase and amplitude. This is commonly used for digital transmission because digital codes can be mapped to various combinations of phase and amplitude.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website: https://bit.ly/pe-downloads

MITCHELECTRONICS

Learn the basics of electronics with Robin Mitchell

Part 3 – Introducing the op amp

MitchElectronics is a series of projects by Robin Mitchell that introduces beginners to useful, simple, easy-to-understand circuit designs. Each month, he will introduce fundamental components, theory and ideas used in electronics. The series will cover both analogue and digital electronics.

In the previous article, we further explored how the 555 timer integrated circuit (IC) worked, introduced you to some digital logic devices, and looked at how these can be used together to create some interesting projects. Now that we have a solid understanding of some basics, it's time to explore the most important analogue IC, the operational amplifier – typically shortened to 'op amp'.

Introduction

So far, we have created *passive* analogue circuits, which can reduce a voltage or divide the flow of current, but they can't amplify it. For example, potential dividers take an input voltage and reduces it in a predictable manner across a number of resistors. But how can we take a small voltage and make it bigger – ie, amplify it? To do this, you need to use *active* components. The fundamental active component is the transistor, which we will of course explain, but later in this series. It's actually easier to start off with a device made up of many transistors and to treat it as a simple amplification block without worrying too much about what goes on under the hood. That amplification block is the op amp, and in this article we will explore how it works, along with a number of sensors that we can use to detect light, temperature and sound.

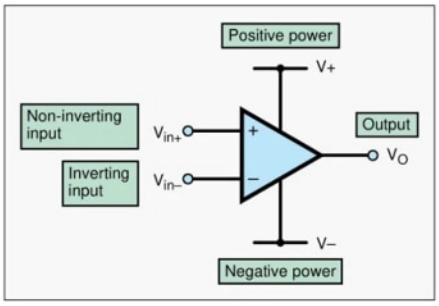


Fig.1. Basic schematic symbol for an operational amplifier, or 'op amp' for short.

What is an op amp?

The op amp is a cheap, flexible and easy-to-use voltage amplifier, which is found in an extraordinary range of applications and circuit configurations. It can be used to amplify signals, compare signals, add/subtract voltages, build filters and oscillators and much more. The basic schematic for the op amp can be seen in Fig.1.

Op amps themselves are not a single component, but a complex IC made up of transistors, resistors, diodes and capacitors. The first op amps were built using thermionic valves and were primarily designed to perform mathematical *operations* in analogue computers – hence the label 'operational' amplifier. They were certainly useful, but they were physically large, expensive and power hungry, a world away from the cheap, tiny efficient devices of today. (As an aside, if you read Jake Rothman's recent *Audio Out* articles you can get an idea of how to build an op amp from modern discrete components. Fig.2 shows the *MitchElectronics Discrete Op Amp* which uses transistors and resistors to build a complete op amp. Do note that the *MitchElectronics Discrete Op Amp* is an educational circuit and does not produce a particularly good op amp. It is designed to teach how an op amp works, not create a precision circuit like Jake's excellent design.)

Fig.2. Discrete Op Amp kit from MitchElectronics

Early IC designers realised that a small, inexpensive op amp offered many advantages and it was one of the first designs that was turned into an IC. Thanks to this integration, highly complex op amps can be fitted onto the tiniest piece of silicon, consuming little power and able to operate at very high frequencies.

Ideal op amp

When first looking at how op amps work, we use an imaginary model called the 'ideal op amp'. This helps us get up and running with designing, building and troubleshooting *real* op amp circuits. Once you get the hang of the ideal version you are in a good position to take account of the limitations of real devices.

An ideal op amp has two power connections and just three signal connections – two inputs and one output. The inputs are called non-inverting (marked with a '+') and inverting (marked with a '–'), the output is the unmarked third terminal.

All op amps needs a power source, typically a positive and negative rail, although many op amps are happy for the negative rail to sit at 0V. The output is generally limited to a band between the two supply voltages and cannot be greater than the supply positive voltage, or less than its negative counterpart. Op amps are usually low-voltage devices and typical supply voltages are ±15V, +9V/0V or +5V/0V.

The output voltage produced by an op amp is equal to the difference of the two inputs multiplied by its gain value. So the obvious question is what is the gain of the op amp? The surprising answer is that by and large you don't know! It is not a well-defined parameter, but even more surprising is the fact that this doesn't matter. All you need to know is that it is very very large. In fact, for our ideal op

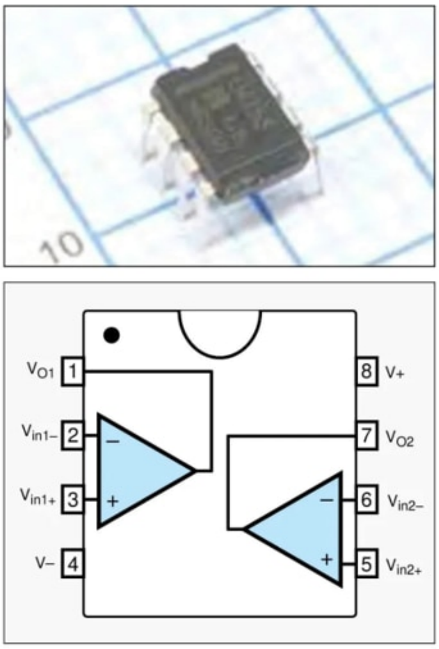


Fig.3.(top) LM358 op amp and (below) its pin layout.

amp it is effectively infinite, but let's dial that down just a tad and call it at least a 100,000, or a million, if not ten million!

So how does this help us design and build circuits? It leads us to the first of two important rules for using op amps. Remember, we said op amps are low-voltage devices. Let's say we are powering our amp with a 10V supply and its gain is 10,000,000. That means if its maximum output is at 10V then its input – the difference between its two inputs terminals – must be 10 divided by 10,000,000, which is a millionth of a volt, a microvolt, written as $1\mu V$. Now, there are times when you need to manipulate such miniscule voltages, but for many real-world applications a microvolt is a pretty good approximation to nothing, 0V.

This leads us to the first rule: the voltage difference between the two inputs of an op amp can be treated as zero volts.

Our second rule is just as simple. The way an op amp is designed and built its inputs draw no current. Op amp inputs just respond to whatever voltage is applied, but they don't take any current from whatever is connected to them.

These two rules will get you surprisingly far in circuit design, and even when you start to take into account the non-ideal aspects of real op amps, the ideal op amp model is an excellent place to start. However, we need to add one very important caveat. All of the above explanation assumes that you are using the op amp in a particular way – in a negative feedback configuration.

Negative feedback

Feedback – especially negative feedback – is at the heart of a large body of work called 'control theory'. Unfortunately, it is a heavily mathematical discipline, and this is not the place to look into it in any great depth, but the key concept is straightforward: take the output signal, feed it back to the op amp's input, and subtract it from the input signal. This is why you have two inputs in an op amp – the inverting input does the subtracting and is connected, often via other components, to the output and the result is a negative feedback system that turns a poorly defined very-high-gain amplifier into an amplifier with a much lower, but very well defined gain. You effectively trade huge unknow gain for limited, well-understood gain. It's a good trade because op amps have lots of gain to offer and most designs only need gain up to a hundred or so, often much less.

Shortly, we'll show you just how easy it is to use our two op amp golden rules to design an amplifier with a specific, accurate gain value.

Real op amps

We've talked a lot about 'ideal op amps', but what does a real one look like? A famous op amp that most engineers grew up with is called the '741' – it's a venerable design dating back to the late 1960s, and while it is certainly works adequately, it doesn't have the best of characteristics, certainly compared with more modern devices. Instead, MitchElectronics kits use the LM358 op amp (Fig.3) which is a real workhorse of the modern electronics industry. For its price, it has excellent characteristics, low current consumption, and can be used in most non-precision applications. It's a dual device, which means you get two independent op amps in one small package, as shown in the pin connection diagram in Fig.3. Expect to pay 50p for single devices, but you can probably pick them up for less than 20p if you buy 10 or more on eBay. They really are very cheap.

How does a comparator work?

Before we get into the nitty-gritty of designing our first negative-feedback op amp circuit, a small diversion to a useful op amp circuit that *doesn't* use negative feedback or our two golden rules. This first configuration that we will explore is a circuit called the 'comparator' which is so simple it requires no external components. As its name suggests, the comparator compares two voltages, telling you which is bigger or smaller than the other. It's useful if you need to know when a particular voltage – perhaps the output of a temperature sensor – rises or falls above or below a particular voltage.

The basic layout of a comparator is shown in Fig.4. Start by examining the inputs of the op amp being used as a comparator. The non-inverting input is connected to a voltage under test, and the inverting input is tied to a fixed voltage. What we have here is effectively a circuit whose output represents a logic signal indicating which voltage is larger.

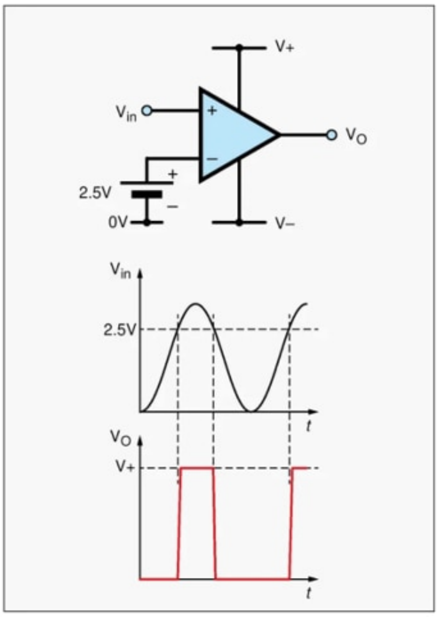


Fig.4. Basic comparator circuit.

If the non-inverting input is larger than the inverting input, then the output will go straight to the positive supply voltage – remember that the output is just a very large multiple of the difference between the two inputs and the output cannot exceed its power supply voltages. Likewise, if the non-inverting is smaller than the inverting input, then the output will drop to the negative supply voltage. In the case of the design shown in Fig.4, our inverting input is connected to a 2.5V supply, so as the non-inverting input rises above 2.5V, the output will switch to 9V, and if it falls below 2.5V, then it will drop to 0V.

Recalling last month's article where we described how potential dividers and potentiometers work, we can replace the fixed reference comparison voltage on the inverting input with a potentiometer to create a comparator circuit that has an adjustable switching point. Fig.5 shows how a potentiometer can be used to adjust this detection level.

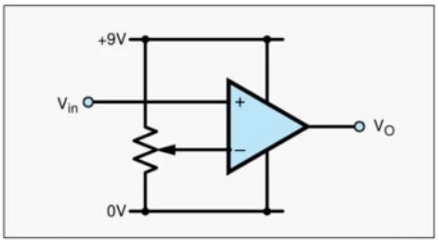


Fig.5. Comparator circuit using a potentiometer to set switching level.

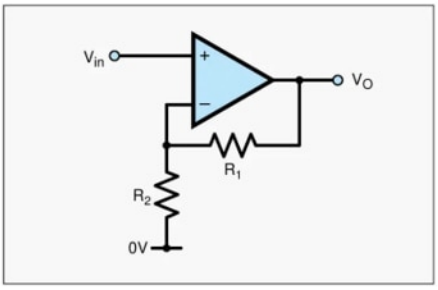


Fig.6. Op amp non-inverting amplifier.

How does a non-inverting amplifier work?

Now let's dive into our first op amp circuit that uses negative feedback – the non-inverting amplifier. This is a configuration that turns a regular op amp into a practical amplifier with a *positive* configurable gain. As the name suggests, the gain of a non-inverting amplifier is greater than zero, meaning that the sign of the voltage is preserved – a positive voltage is amplified into a bigger positive voltage, and a negative voltage is amplified into a more negative voltage. (By contrast, in a future article we will meet the inverting amplifier, where the gain is less than zero, which means that the sign of the voltage is reversed – a positive voltage is amplified into a bigger *negative* voltage, and a negative voltage is amplified into a bigger *positive* voltage.)

The circuit for a non-inverting amplifier is shown in Fig.6. It uses a potential divider on the output that feeds back into the inverting input terminal of the op amp – hence negative feedback. It's this connection between the output and the inverting input that controls the gain of the circuit, via the ratio of the two resistors, summarised in the following equation:

$$Gain = 1 + \frac{R_1}{R_2}$$

But how is this equation derived? This is where our golden rules come into play. If we assume that the internal gain of the op amp is huge and that the output of our amplifier circuit is small (a few volts), then the voltages at the two inputs must be the same value, since even the tiniest difference would result in a very large output.

The voltage at the inverting input terminal is provided by the potential divider circuit comprising R1 and R2, which is driven by the output voltage of the op amp. Thus, we can say that the voltage at the inverting input terminal is:

$$V_{in-} = V_o \times \frac{R_2}{R_1 + R_2}$$

But we know that this must be equal to the voltage on the non-inverting input, so we can say:

$$V_{in+} = V_{in-} = V_o \times \frac{R_2}{R_1 + R_2}$$

Rearranging, we can get the gain (the ratio of the input to the output voltage):

$$\frac{V_{in+}}{V_o} = \frac{R_2}{R_1 + R_2}$$

Which can be rewritten as:

$$\frac{V_o}{V_{in+}} = \frac{R_1 + R_2}{R_2}$$

Simplifying the equation results in:

$$\frac{V_o}{V_{in+}} = \frac{R_2}{R_2} + \frac{R_1}{R_2} = 1 + \frac{R_1}{R_2}$$

And thus the gain – the ratio of output to input is:

$$Gain = 1 + \frac{R_1}{R_2}$$

When selecting resistors for an op amp circuit, it is important that the resistors are not so small as to result in large current flow, but not so large that the op amp doesn't have sufficient current to operate. Remember, while an ideal op amp consumes no current, a real op amp does require a minimum level of current to operate, albeit very small (microamps to nanoamps). It is often best to choose resistors in the range from 1kΩ to 100kΩ.

Let's design a couple of non-inverting amplifiers. Say you need to amplify a signal by a factor of 2.5, what resistors would you choose? We simply set the gain equal to 2.5:

$$Gain = 2.5 = 1 + \frac{R_1}{R_2}$$

We subtract 1 from each side so that:

$$\frac{R_1}{R_2} = 1.5$$

And that gives us a nice R1:R2 ratio. We could have R1 = 1.5kΩ and R2 = 1kΩ, or R1 = 15kΩ and R2 = 10kΩ

If we need an amplifier with a gain of say 52.8 then we just repeat the process with different numbers:

$$Gain = 52.8 = 1 + \frac{R_1}{R_2}$$

Resulting in:

$$\frac{R_1}{R_2} = 51.8$$

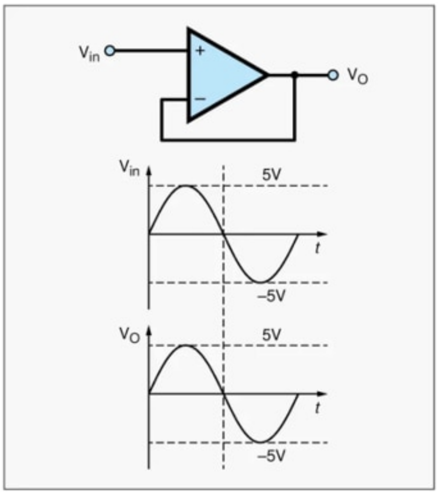


Fig.7. Op amp unity-gain buffer circuit and example output. Note that the gain is precisely 1 for this amplifier..

At this point you will have to do a little experimentation with the available values of resistors, and you may not hit exactly 51.8, but you might decide – for example – that 62kΩ/1.2kΩ = 51.67 is close enough (it's about 0.25% out). Do remember that unless you (unnecessarily) invest in high-precision resistors the components you use typically have a precision of around 1% (or worse), so chasing ultra-close resistor ratios is a fool's errand!

How does a unity-gain buffer work?

A particularly common variant of the non-inverting amplifier is called the unity-gain amplifier, often referred to as a buffer. It is a non-inverting amplifier with a gain of exactly one. However, unlike other non-inverting amplifiers, a unity-gain buffer doesn't require any external resistors to work, and only needs the output directly connected to the inverting input terminal, as shown in Fig.7.

This configuration is useful when measuring extremely sensitive voltage sources that are highly susceptible to the tiniest change in resistance or current. Buffers are used to separate sensors from driver circuits so that no matter how much current a driver circuit is consuming, the sensor will not be affected.

If we draw out a unity-gain buffer as a non-inverting amplifier, we can see why its gain is 1. Fig.8 shows a non-inverting

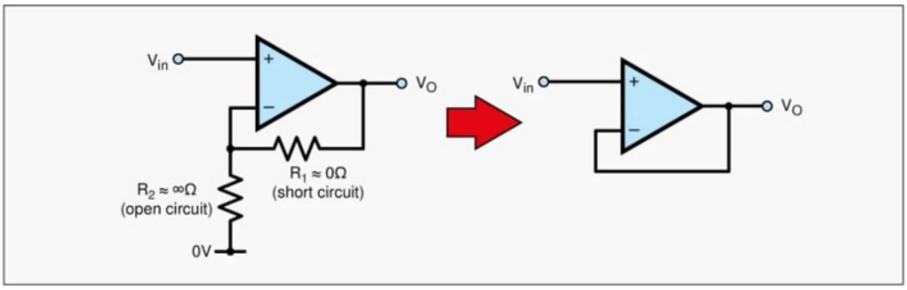


Fig.8. Non-inverting amplifier as a unity-gain buffer.

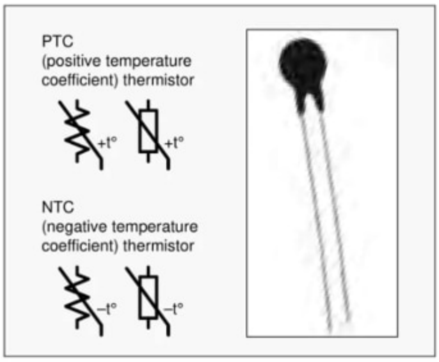

PTC
(positive temperature coefficient) thermistor
+t°
+t°
NTC
(negative temperature coefficient) thermistor
–t°
–t°

Fig.9. Thermistor schematic symbol and real-world example.

amplifier with two resistors whose values are 0Ω and 'infinite' Ω. The 0Ω resistor represents a straight wire connecting the output to the inverting input terminal input, a short circuit. On the other hand, the infinite-ohms resistor represents an open circuit or disconnection.

If we plug these numbers into the non-inverting amplifier equation (remember that zero divided by anything is always zero), we get the following.

$$Gain = 1 + \frac{R_1}{R_2} = 1 + \frac{0}{\infty} = 1$$

It's a simple, handy circuit that you will definitely use, and now you know how it is designed.

Sensors

We have looked at three important op amp circuit configurations, so let's put them to good use and learn how three different sensors work, and how they can be used in circuits. All the sensors and op amp circuits shown here are available from the MitchElectronics Sense Range (as well as the light and sound alarm circuits).

How do thermistors work?

Thermistors are resistors whose resistance greatly depends on their temperature. While the resistance of all materials depends on their temperature, thermistors are unusual in that the variation of resistance in relation to their temperature is much more pronounced compared to say a piece of metal. For example, heating a piece of copper a few degrees would result in a negligible change in resistance, but for a thermistor, this temperature change could easily be 1kΩ. The schematic symbol and an example of a thermistor are shown in Fig.9.

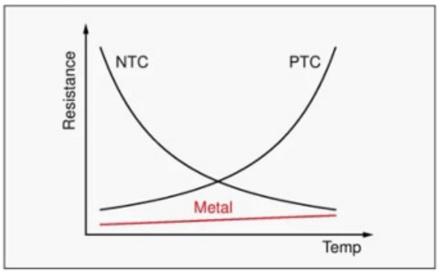


Fig.10. Graph showing PTC and NTC thermistor resistance vs. temperature. Although thermistors are not very linear (curved-line response), they are much more sensitive to temperature compared with metals.

Two main types of thermistors exist, positive temperature coefficient (PTC) and negative temperature coefficient (NTC). It is important that you select the right one for your circuit, as they work in the opposite way to each other. A PTC thermistor has a positive correlation with temperature, so an increase in its temperature results in an increase in its resistance. An NTC, however, has a negative correlation – an increase in its temperature results in a decrease in its resistance. The graph for these resistances can be seen in Fig.10.

All thermistors have a nominal resistance at a specified temperature, typically at 25°C, but the amount by which a thermistor responds to temperature changes can vary. For example, a 1kΩ NTC thermistor will have a resistance of 1kΩ at 25°C, but how much this changes with temperatures will depend on its construction and composition – you need to check the device's datasheet or specification to find the characteristics of your chosen device.

A thermistor on its own isn't very useful, which is why they are commonly used in potential divider circuits. With the addition of a fixed resistor, a potential divider can be constructed whose output voltage depends on the temperature of the thermistor, and the selection of either a PTC or NTC will change how the potential divider reacts to changes in temperature. Fig.11 shows how thermistors can be used in potential divider circuits to create these responses. (To understand how this circuit operates you need to know how a potential divider works – see last month's article for an in-depth explanation.)

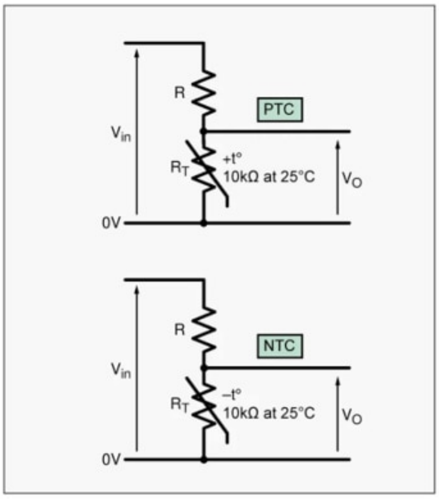


Fig.11. Potential divider circuits using a PTC and NTC thermistor.

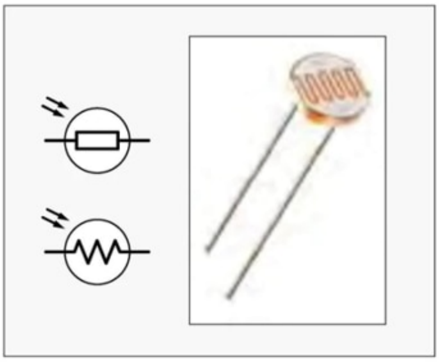


Fig.12. LDR schematic symbol and example component.

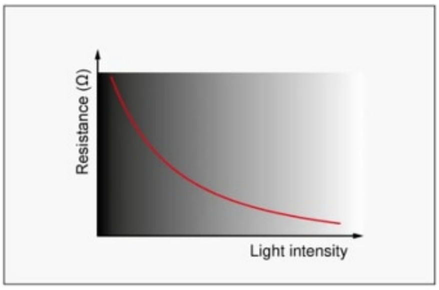


Fig.13. LDR illumination-resistance graph – more light leads to lower resistance.

How do light sensors work?

Light sensors, as the name suggests, are sensors that react to changes in light levels, and come in numerous variations. The most common light sensor that engineers will be familiar with is the light-dependent resistor, or LDR for short, with the schematic symbol shown in Fig.12.

As the amount of light falling on an LDR *increases*, its resistance *decreases*, which gives LDRs a negative response, as illustrated in the graph in Fig.13. This makes LDRs ideal for using in potential divider circuits, just like thermistors. However, most LDRs (if not all) use toxic compounds including cadmium, which are restricted by all kinds of legislation around the world (eg, RoHS and REACH).

Because of this, MitchElectronics recommends makers and engineers avoid LDRs and switch over to photodiodes (which all MitchElectronics kits use). Photodiodes are light-sensitive diodes that produce a tiny amount of current when light falls on them. See Fig.14 for their schematic symbol and an example of a component.

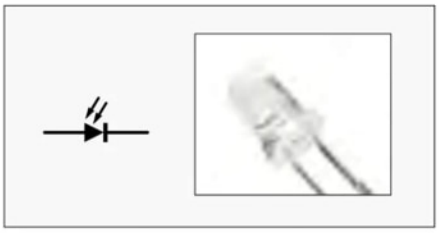


Fig.14. Photodiode schematic symbol and component.

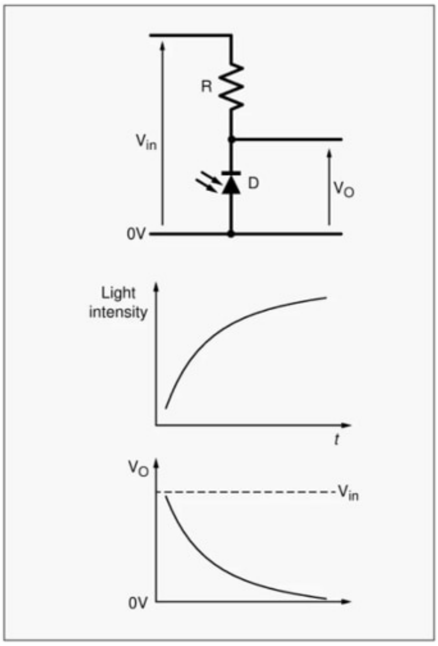


Fig.15. Photodiode potential divider circuit and its output response.

When using photodiodes, we don't use them as a current source, but instead, we use them in reverse-bias mode. What this means is that instead of connecting the anode to a positive voltage and the cathode to a negative voltage, we flip the diode polarity. Why on earth would we do this?

Well, it turns out that when a photodiode is in reverse-bias mode in the dark then it doesn't conduct electricity, but when it is illuminated with light, it starts to conduct thus it effectively goes from near-infinite resistance to some finite level of resistance. If used with another resistor, it becomes possible to create a potential divider circuit so we can produce a voltage that depends on the amount of light falling on the photodiode. Fig.15 shows an example of how a photodiode can be used in a potential divider circuit.

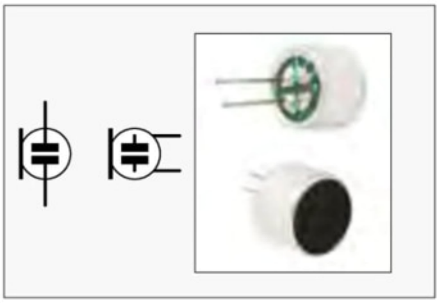


Fig.16. Schematic symbol for the electret microphone and real-world component.

While it is possible to calculate the exact resistor value needed, doing so is a rather complex procedure due to the diode's mathematically complicated relationship between light levels and current conduction. Fortunately, you can bypass all this complexity with a potentiometer to tune a circuit so that its sensitivity can be adjusted in-circuit. Additional prototyping on a breadboard to identify a suitable value resistor is also appropriate, and typical values will range from 1kΩ to 10kΩ.

How do electret microphones work?

After temperature and light, another common measurement parameter is sound level. Measuring sound is the job of microphones, which come in a variety of technologies and price points. Of all the microphone technologies out there, the electret microphone is by far the most popular due to its low price, small size and ease of use. The electret microphone (show in Fig.16) integrates a transistor amplifier and capacitor-based diaphragm into a single package, requiring only two connections.

While the workings of the internal transistor won't be explored here (we will cover transistors in a later issue), the basic principle behind the electret microphone is that as sound hits the capacitor-based diaphragm, a small change in electric charge causes the internal transistor to become more conductive – ie, its resistance drops. So, again, we can connect our sensor (the electret microphone) into a potential divider circuit so that as the sound level rises the potential divider voltage drops – see Fig.17 for the basic circuit configuration.

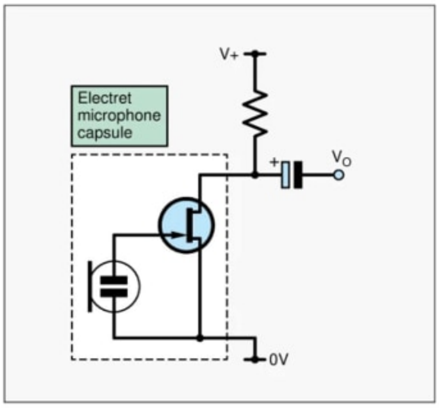


Fig.17. Internal schematic of an electret microphone and potential divider circuit with DC blocking capacitor.

Because of its inverting nature and the fact that there is a large DC component in the electret microphone's output signal, electret microphones circuits almost always incorporate a DC-blocking capacitor. The blocking capacitor removes the DC component but preserves the sound signal. Selecting the resistor value in an electret microphone potential divider circuit is not a precise science and is somewhat more experimental. General values for this resistor are between 1kΩ and 10kΩ.

I hope you can see from just these three examples that the time and effort we invested in understanding the potential divider circuit last month was well worth it!

Fig.18. The MitchElectronics Sense Range collection of circuits.

Top row (l-r): IR Range, IR Sensor and Light Sensor; botom row (l-r): Sound Sense, Temperature Sensor.

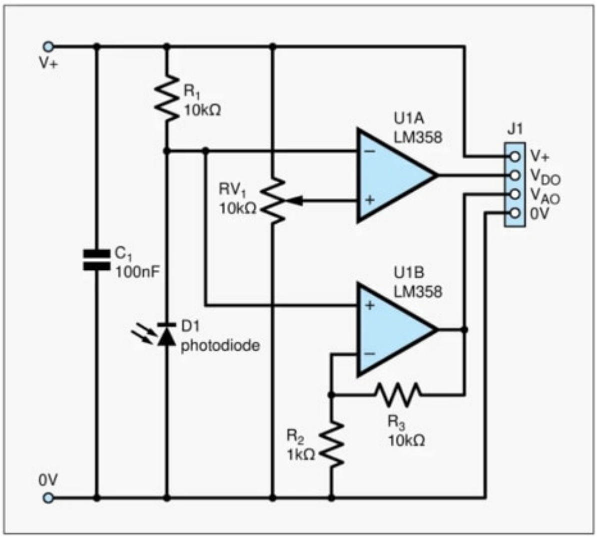


Fig.19. *Light Sense* kit circuit diagram.

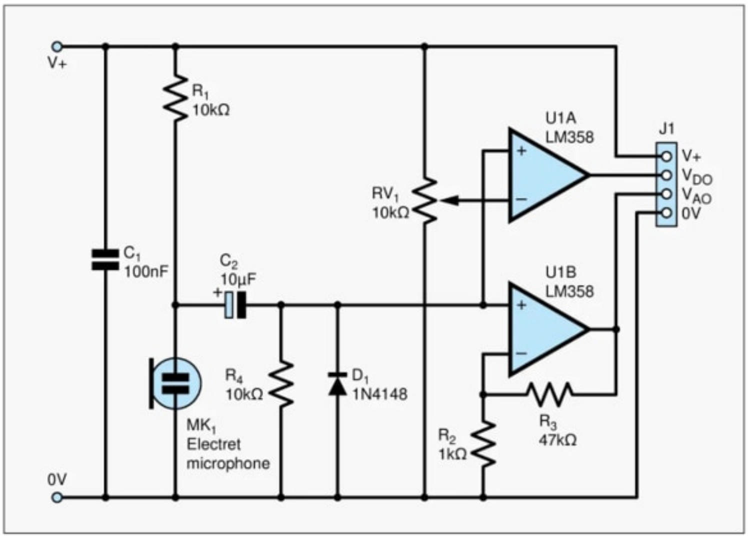


Fig.21. *Sound Sense* kit circuit diagram.

The MitchElectronics Sense Range

Light Sense

Now that we have covered op amps, their configurations and some sensors, we can explore the MitchElectronics Sense Range; Fig.18 shows the various modules in the range. These kits are designed to act as modules that can be used with other circuits, and each module has its own unique type of sensor.

Most of the Sense Range kits have the same circuit setup; a non-inverting amplifier for amplifying the signal of a sensor, and a comparator to act as a digital level detector. The schematic for the *Light Sense* is shown in Fig.19.

We can see in this schematic that there are two op amps inside the LM358 IC, labelled as U1A and U1B; both op amps are powered by the same voltage source. U1A is configured as a comparator, while U1B is configured as a non-inverting amplifier whose gain is determined by R3 and R2.

The photodiode D1 is in a potential divider circuit with resistor R1, and in this configuration, as the amount of light falling on D1 increases, the voltage across D1 will decrease as its resistance falls. As a light-detecting circuit, that response is somewhat counterintuitive, so in our comparator circuit, instead of connecting the voltage across D1 to the non-inverting input terminal of the op amp U1A, we have connected it to the inverting input terminal.

By connecting the potentiometer RV1 to the non-inverting input terminal, we can set what level of light will result in the comparator triggering, and because we have connected the sensor's output to the inverting input, the comparator's output will go high when light *above* a certain level is detected. Fig.20 shows the output of the comparator depending on the light level and different potentiometer settings.

Op amp U1B has been configured as a non-inverting amplifier with feedback resistors of 10kΩ and 1kΩ. If we plug these numbers into our gain equation, we find that the amplifier has a gain of 11. As the photodiode in this circuit produces a low voltage for light detection, this amplifier is only useful for detecting high levels of brightness because when there is no light, this amplifier will be saturated (ie, the output will be equal to the supply voltage).

Finally, capacitor C1 is called a 'decoupling capacitor' – it smooths out the power rail during rapid switching. Decoupling capacitors are recommended for any circuit using ICs, as fast switching circuits can induce noise into the power rails and interfere with the operation of integrated circuits – not damage them – but cause output errors.

Sound sense

The *Sound Sense* circuit is a little more complicated because the electret microphone needs a bit of extra design consideration. Fig.21 shows the *Sound Sense* schematic, and you can see it is similar to the *Light Sense* design we just analysed.

Again, op amp U1A is a comparator and U1B is a non-inverting amplifier. However, there are several differences that relate to how the sensor works and

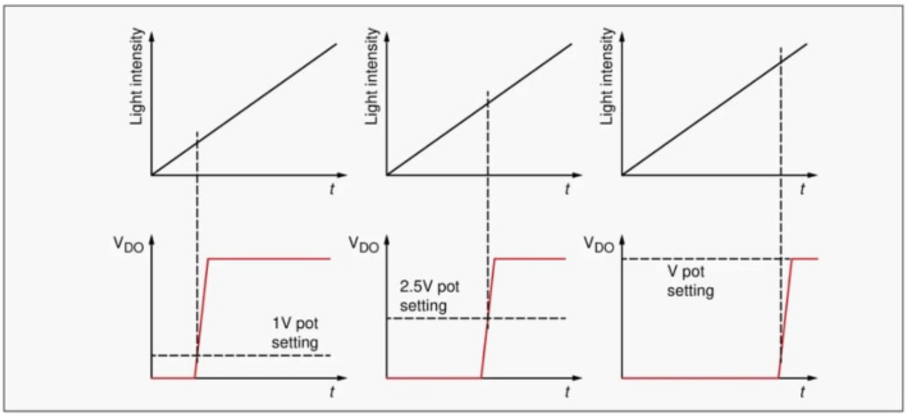


Fig.20. Comparator output vs. light level and potentiometer setting. The higher the potentiometer output voltage setting, the more light is required to switch the comparator.

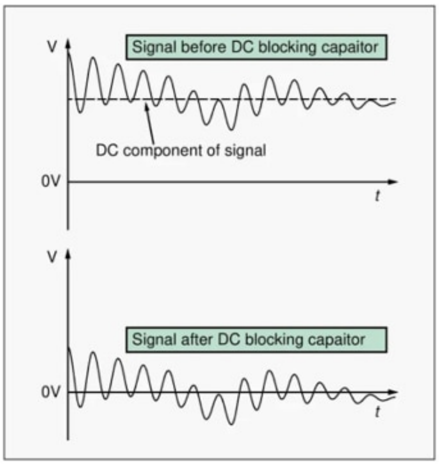


Fig.22. Signal from *Sound Sense* electret microphone vs. same signal after passing through the DC blocking capacitor C2.

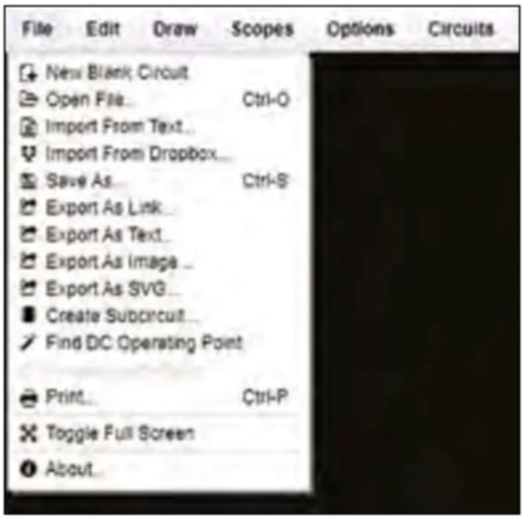


Fig.23. Menu options in CircuitJS.

the gain of the non-inverting amplifier. The electret microphone is in a potential divider circuit with R1, but this circuit results in an inverse response (ie, *louder* sound results in a *smaller* voltage across MK1). Despite this negative response, because the signal from this potential divider has been AC coupled to the op amps, only the *change* in signal is detected, thus eliminating a negative response. Fig.22 shows the output of the electret microphone potential divider, and the resulting AC signal after passing through C2.

The next section of circuitry is diode D1 and resistor R4. After the signal from the electret goes through DC-blocking capacitor C2, it contains both a positive and negative component. The negative (<0V) portion of the signal can cause the LM358 to exhibit unusual behaviour because here, its negative power rail is 0V. By connecting a diode in reverse-bias mode between the AC signal and ground, any negative signal greater than 0.6V is removed. Resistor R4 ensures that no DC signal can form across C2 by discharging the negative plate of C2. Without R4, the capacitor would slowly charge, resulting in a large voltage and suppressing the microphone signal.

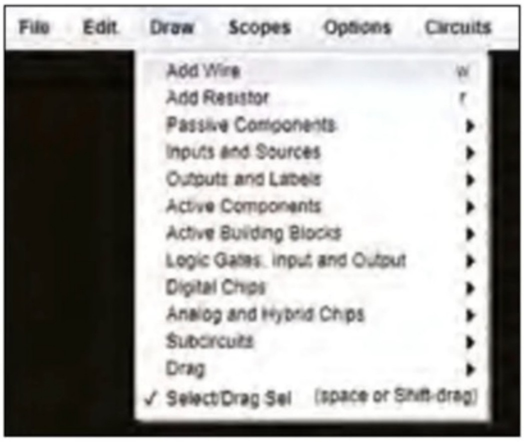


Fig.24. Draw menu with add resistor option.

Comparator U1A, unlike in the *Light Sense*, has its non-inverting input connected to the AC-coupled signal (via the DC-blocking capacitor) from the electret microphone, and its inverting input connected to a potentiometer. This means the comparator will output a high voltage if the voltage from the AC-coupled stage exceeds the potentiometer voltage, thus indicating the presence of sound.

Finally, the non-inverting amplifier U1B has R3 = 47kΩ and R2 = 1kΩ, which results in a gain of 48. It needs more gain than the *Light Sense* because the microphone produces a smaller signal.

Building and testing the projects

To learn how to build and test these electronic circuits, see the previous editions of *Practical Electronics* (December 2023 and January 2024).

The Falstad Circuit JS Simulator

In the last article, we mentioned how simulations can be used to help prototype circuits before making them in real life, which can save time and expense. We also learned that simulations are excellent for demonstrating how circuits operate, allowing you to probe various components, measure voltages and currents, and plot these figures on charts against time. But of the many simulators that exist, which one should you use?

LTSpice is a good option as it's free and comes with a wide range of parts, but it does involve a steep learning curve, making it a challenge for beginners. Others, such as Multisim, are great for beginners, being simple to use, but they aren't free, so possibly not ideal for those of you just starting out in electronics.

All MitchElectronics kits take advantage of a browser-based simulator called CircuitJS, created by Falstad. This simulator is not only free, but runs in an Internet browser and is simple to use. To load this simulator, visit: **https://bit.ly/ME-CircuitJS**

Create a new file

The first step you will need to do is create a new blank simulation: click File > New Blank Circuit (see Fig.23). Under this menu option, you can also save circuit designs, load circuit designs and export your circuit as an image file.

Drawing components

The second step you will need to do is add components. You can do this by clicking the Draw option in the menu bar, and searching for the component you want to place (in this case, lets place a resistor which is found under Draw > Add Resistor, see Fig.24). Once selected, you need to click and drag the mouse to generate the length of resistor you want.

Drawing wires

Once you have placed your components you need to draw connecting wires. Again, navigate to Draw and select the first option 'Add Wire'. In CircuitJS, you can only connect components and wires at their end terminals (indicated by white dots). This means that if there are multiple components connected to the same wire, you will need to draw individual segments between components, as seen in Fig.25. (You can see if a junction isn't connected properly because it will be red instead of white.)

Simulation controls

Once you have a basic circuit built, you need to start (and stop) a simulation. To do this, click the Run / STOP button found in the righthand pane of the simulator (see Fig.26). Here you will also find two additional options, Simulation Speed and Current Speed. Adjusting the simulation speed will either slow down or speed up the simulation, while the Current Speed option will change how fast the current icons flows around the circuit (represented as small yellow boxes that run along wires).

Current flow

A really unique feature of the CircuitJS simulator is that it shows both voltage and current flow simultaneously in a graphical animated form. This not only helps to visualise how current is flowing around a circuit, but also helps in understanding how circuits work – see Fig.27.

The colour of a wire indicates the voltage at that point, while small yellow squares represent current flow. The greener a wire is, the more positive its voltage, and the redder a wire is, the more negative. The direction and speed indicate which way current is flowing and how large that current is.

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All the kits/parts described in the series are available from:
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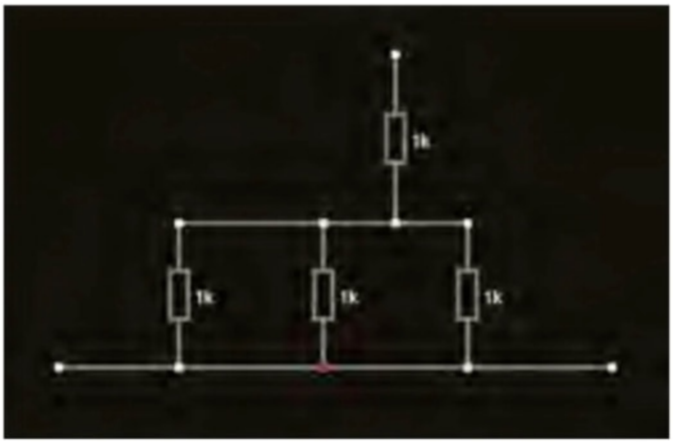

Fig.25. Wire connections, including a disconnect (red junction).

Note that these colours and speeds are entirely relative, meaning that they only represent the situation of a circuit as opposed to indicating an absolute value.

Give CircuitJS simulator a try, it's a fun and intuitive way of learning and understanding electronics.

Conclusion

Op amps are vital components in the field of electronics thanks to their low cost, ease of use, flexibility, excellent characteristics and small size. With just a handful of external resistors and other parts, op amps can be made to do all kinds of things, and the three circuits that we covered in this article are just a sample of the many possible configurations.

Sensors also play a critical role in electronics. Without them, we would not be able to make devices that respond to their environment. By combining sensors with op amps, we can create all kinds of useful circuits that can control other circuits, both analogue and digital.

If you want to get started with sensors and op amps and would like to help support the work we do at MitchElectronics, then consider heading over to **www.mitchelectronics.co.uk** where you can find inexpensive kits, instructions, guides and other resources that will aid you in building your own electronic projects.

In the next article, we will make our first piece of test equipment, a *Simple Function Generator*, and learn how to make square and triangular waves that can be used to test other projects.

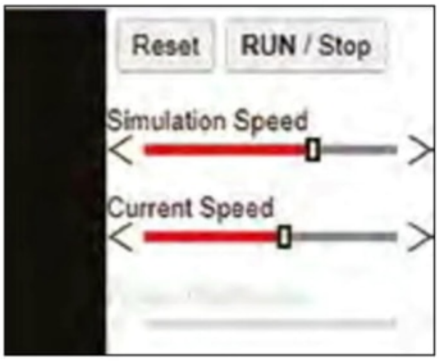

Fig.26. CircuitJS simulation controls.

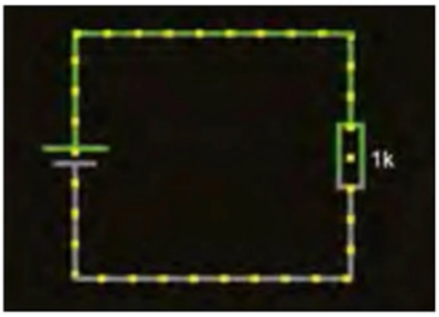

Fig.27. Running a CircuitJS simulation showing positive voltage and current flow.

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IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
HP8903A/B	Audio Analyser	£750 – £950
HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£400
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
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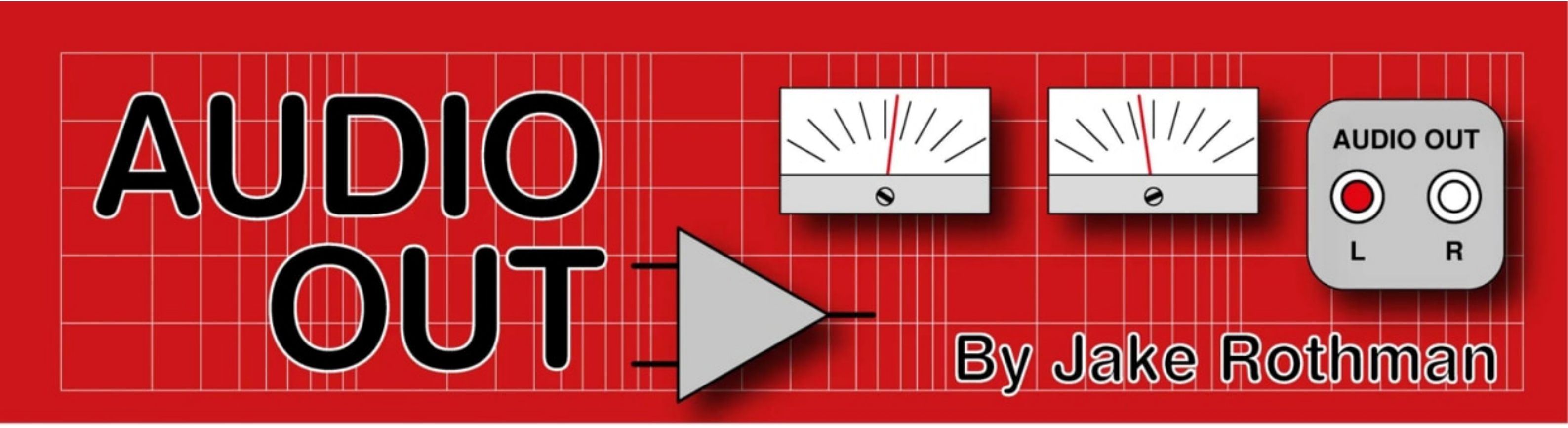
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700

Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHz	£295
Marconi 2945/A/B	Communications Test Set Various Options	POA
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65

HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

HP/Agilent HP 34401A Digital
Multimeter 6½ Digit £325 – £375

Marconi 2955B Radio
Communications Test Set – £800



AUDIO OUT

By Jake Rothman

Back to the buffers – Part 1

Last month, we completed the *Discrete Op Amp* design. An obvious application for any op amp – precision or otherwise – is as a buffer. However, it's generally not necessary to use the level of complexity we employed in the *Discrete Op Amp* design for a buffer, so this month so we'll look at some high-quality discrete buffer circuits.

Hitting the buffers

While electronic engineers prefer the term 'voltage follower', audio engineers use the term 'buffer', since they are usually used to isolate one stage from another. The basic requirements for a good buffer are:

- High input impedance
- Low output impedance
- Good current delivery.

Since a buffer only has a voltage gain of one, or 'unity', the massive amount of open-loop gain of an op amp is not needed to obtain very low distortion. Most buffers rely on the 100% negative feedback that occurs inside the device. This works by holding the voltage constant between the input and output. The input voltage is reflected in the load resistor, as shown in the emitter follower in Fig.1. This means that there is an effective 'open-loop gain' for a single transistor. The transconductance (voltage in for current out) reduces the distortion and output impedance. The transconductance is less for JFETs which means the buffer's total harmonic distortion (THD) is higher when used as source followers (Fig.2). However, the JFET's transfer function (voltage in versus current out) curve is less abrupt – essentially a square law initially (in theory) rather than the exponential curve generated by bipolar transistors. This curve difference is akin to the old triode vs pentode sound debate in Hi-Fi circles. The idea is that the greater profusion of lower-order harmonics generated by the slower rate of slope change in the JFET circuit (compared to the bipolar version) gives a less harsh sound. The clipping is also softer as well. I use this to good effect in the FET input buffer stage of the Colorsound Powerboost guitar preamp pedal. As far as Hi-Fi buffers are concerned, this is not good, Hi-Fi buffers need to be as linear as possible.

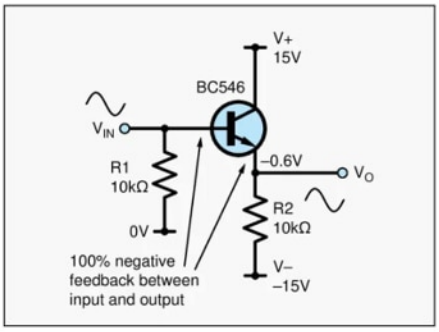


Fig.1. Simple bipolar emitter voltage follower or buffer.

Instability

All buffers are prone to oscillation or high frequency instability at elevated frequencies (MHz). Often, the oscillation frequency is so high that it manifests itself as a thickening of the scope trace. This occurs when capacitance is present on the output. This capacitance can be from a screened cable or simply a scope probe. It can be isolated with a low-value series resistor of typically 22Ω to 100Ω. Sometimes this is bypassed with a small inductor to get the output impedance at audio frequencies back down to a few ohms.

The root cause of instability is the 100% negative feedback normally present. Strangely, another factor is 'negative output resistance' at high frequencies, which can be generated in some transistors. This can cause the gain to rise above unity. Also, the input wiring inductance, along with the base-emitter capacitance of the transistor – JFET or bipolar, but especially the latter – can result in oscillation. This can be fixed with 'grid-stopper' R1 and a capacitor shown in Fig.2

One old buffer to another

The 'textbook' two-component buffers shown in Fig.1 and Fig.2 have distortion in the region of 1 to 5% at line level. This is 0dBm or 2.2$V_{pk\text{-}pk}$/775mV_{RMS} into 600Ω, and all distortion measurements are made under these conditions. Both of these approaches were used successfully in early solid-state Hi-Fi when the signal level was around 100mV_{RMS} and loads were high, typically 47kΩ.

Another common buffer problem is asymmetric current delivery, where the circuit sources or sinks current more easily in one direction rather than the other. When this happens one side of the output waveform clips first into low-impedance loads. A buffer may only have a voltage gain of one, but the internal gain required may be over 400, and this cannot be achieved by a single transistor if low distortion is also required.

Bi-polar transistor also have a non-linear input impedance which causes distortion when fed from high source impedances, such as when following a volume control or as part of a filter. JFETs do not suffer from this defect, but come with extra circuit complexity. Fortunately, all these problems can be overcome.

Constant current

The first improvement to the basic buffer shown in Fig.1 and Fig.2 is to upgrade the load resistor to a constant-current load. The basic load resistor is effective-

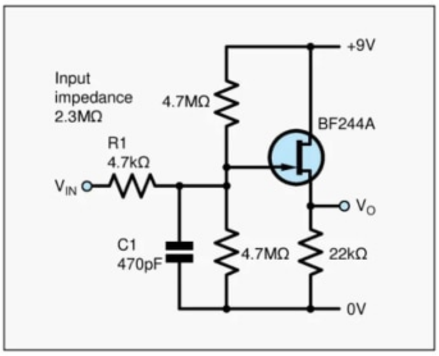


Fig.2. Simple JFET buffer used on input to Colorsound Powerboost pedal. Distortion is very high, around 5%, but gives a bright sound on high-inductance guitar pick-ups due to its high input impedance.

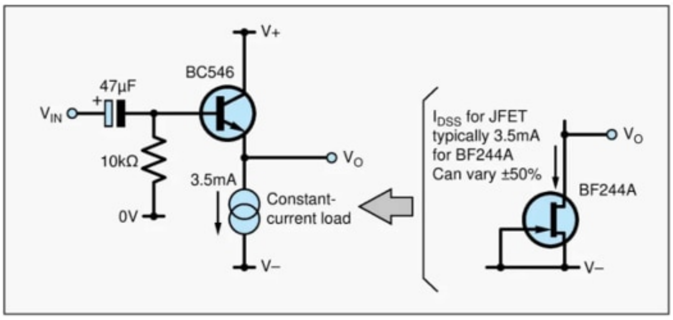

V+
BC546
47µF
+
V_{IN}
10kΩ
V_O
3.5mA
0V
Constant-current load
V–
I_{DSS} for JFET typically 3.5mA for BF244A Can vary ±50%
V_O
BF244A
V–

Fig.3. The addition of a constant-current load gives multiple improvements. Distortion is 1% with the BC546B. A FET or 3.5mA current regulator diode can be used.

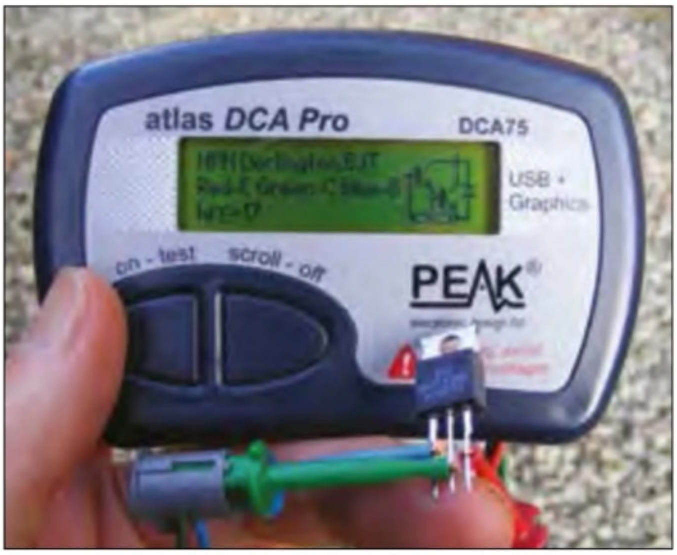

atlas DCA Pro
DCA75
NPN Darlington BJT
Red-E Green-C Blue-B
hFE=17
USB + Graphics
on - test
scroll - off
PEAK

Fig.7. Peak analyser shows why high-power Darlington transistors are not suitable for input devices. The gain is low at low currents (5mA).

ly in parallel with the load to be driven, resulting in over half the available output power being wasted. Changing to the constant-current load shown in Fig.3 means this loss is eliminated. Also, the circuit becomes immune to power supply variations, and has a stable predictable quiescent current. Another advantage is that the gain is closer to unity. With just a resistor the gain can be significantly less than one. Do remember though, to get the full benefit of the active load, its output needs to feed a high impedance. This is the main reason the distortion of a resistive load buffer is poor when driving the standard 600Ω test load.

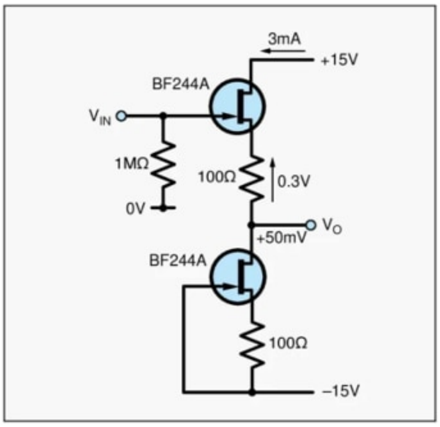

3mA
+15V
BF244A
V_{IN}
1MΩ
100Ω
0.3V
0V
+50mV
V_O
BF244A
100Ω
–15V

Fig.4. Two JFETs can be combined to make an effective buffer. Distortion is 1.1%, but it has a lovely soft clip.

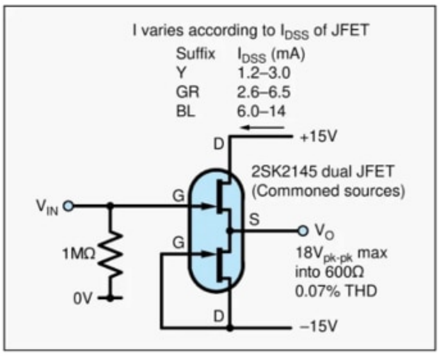

I varies according to I_{DSS} of JFET
Suffix I_{DSS} (mA)
Y 1.2–3.0
GR 2.6–6.5
BL 6.0–14
+15V
D
2SK2145 dual JFET (Commoned sources)
G
V_{IN}
S
V_O
G
1MΩ
18V_{pk-pk} max into 600Ω
0.07% THD
0V
D
–15V

Fig.5. Dual-JFET buffer has much lower distortion (0.07%) due to the better matching, causing some kind of curve cancellation.

JFET followers

Using a JFET results in a linear high input impedance of over 1MΩ, defined by the input resistors. This quality is particularly useful for active filters using low-value polystyrene capacitors along with high-value resistors.

A popular JFET follower configuration is shown in Fig.4. This circuit uses a couple of BF244s. However, it exhibits disappointing distortion into a 600Ω load, 1.1% at 0dB. If the load impedance had been higher, say around 10kΩ instead of 600Ω then it would have been reduced to 0.1%. The problem seemed to be mismatching of the JFETs. When these were replaced with a dual matched pair device, as shown in Fig.5, the distortion dropped to 0.07% into 600Ω.

Darlington configuration

A good compromise if JFETs are to be avoided for cost, availability or distortion reasons, is to use a small-signal Darlington transistor, which only costs around 30p. This increases the input impedance to 90kΩ with a 100kΩ input bias resistor, as shown in Fig.6. An MPSA13 Darlington works here, up to 30V total rail voltage. For higher rails, the MPSA29 can be used, which is rated at 100V. More common high-power Darlington devices, such as the BD680, won't work here because of their low H_{fe} at low operating (emitter) currents of 1-5mA. This is because they have internal resistors shunting the base-emitter junctions. The Peak DCA75 gives an H_{fe} reading of around 16 to 40 with these devices (as shown in Fig.7) and around 16,000 for the MPSA29.

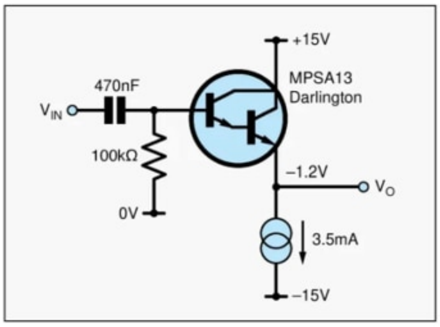

+15V
MPSA13 Darlington
470nF
V_{IN}
100kΩ
0V
–1.2V
V_O
3.5mA
–15V

Fig.6. Darlington input can increase input impedance compared to a single transistor.

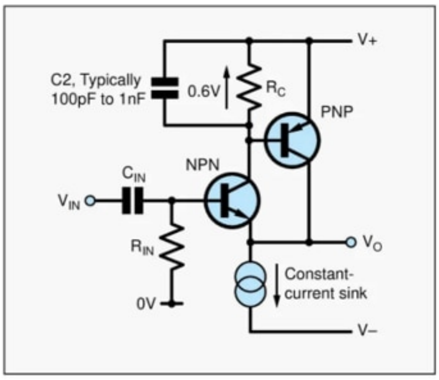

V+
C2, Typically 100pF to 1nF
0.6V
R_C
PNP
NPN
C_{IN}
V_{IN}
R_{IN}
V_O
Constant-current sink
0V
V–

Fig.8. The CFP or Sziklai (pronounced 'sick-lie') follower gives lower distortion than the Darlington version, but is more prone to instability and often needs a capacitor across the first transistor's collector load resistor.

Complementary pair

An improvement on the Darlington transistor circuit is to use two opposite polarity transistors, multiplying together each individual device's current gain. This is called a compound follower pair (CFP) or 'Sziklai pair', as shown in Fig.8. In this case there is 100% negative feedback across two transistors. This improves linearity almost a hundred-fold compared to a single device, but makes oscillation more likely, so stabilising capacitor C2 is often necessary. The input device can also be a JFET, where its higher distortion is greatly reduced.

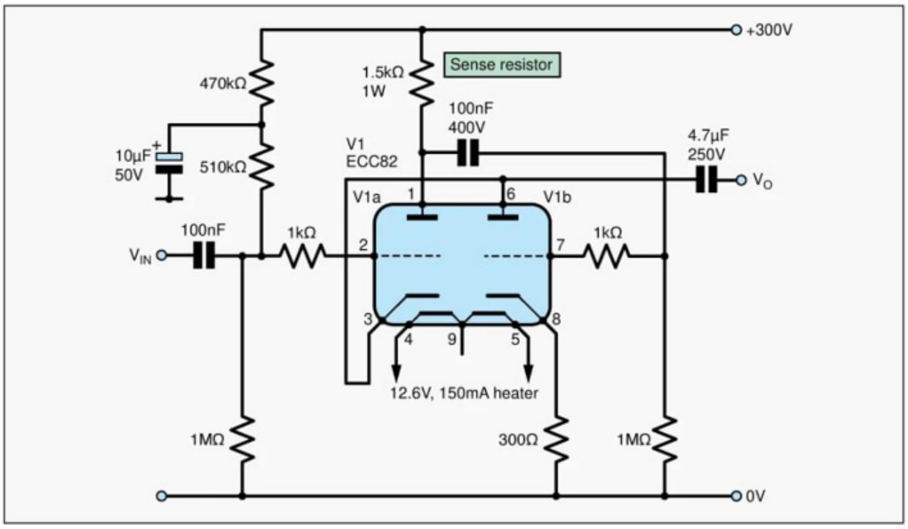

+300V
470kΩ
1.5kΩ
1W
Sense resistor
100nF
400V
10µF
50V
510kΩ
V1
ECC82
4.7µF
250V
V$_O$
V1a
1
6
V1b
100nF
1kΩ
V$_{IN}$
2
7
1kΩ
3
8
4
9
5
12.6V, 150mA heater
1MΩ
300Ω
1MΩ
0V

Fig.9. The valve-based White follower has a modulated current load (V1b). Unfortunately, V1a can suffers from a high heater-cathode voltage possibly causing leakage current, resulting in noise. Note the 1kΩ grid-stopper resistors.

Modulation

The constant-current load's operating current can be modulated to improve efficiency and distortion. One modulation technique is to take a signal from a sense resistor in the power feed to the follower, which gives the required 180° phase reversal. This configuration was called the 'White follower' in the days of valves, and is shown in Fig.9. I first saw this technique applied to transistors in Nelson Jones' *Wideband Oscilloscope Probe* (*Wireless World*, August 1968).

Theoretically, the same output current or load-driving capability can be achieved with half the operating current since it is a form of push-pull operation. Interestingly though, when testing this with my Audio Precision THD analyser, I found there was an optimum amount of modulation for lowest distortion. This point did not coincide with maximum efficiency and was dependent on load resistance and rail voltage. I'm not sure what the relationship is, but there is a distortion null point as the sense resistor is adjusted. Most audio circuits are mains powered, so maximum efficiency is not an important criterion, thus these circuits are tweaked for minimum distortion at normal levels. The distortion was several times greater without current load modulation.

This configuration has the advantage of easy optimisation and does not affect stability. The sense resistor also provides short-circuit protection when sourcing current. The disadvantages are the loss of 1V to 3V of headroom and injection of power supply noise (especially at clipping). However, with a regulated power supply, which any respectable audio system will use, this is not a problem.

The modulated current load can be a FET or bipolar device. With a high-impedance device the coupling capacitor can be small and non-polarised. This is illustrated in Fig.10 and Fig.11 which are almost exact solid-state versions of the valve circuit in Fig.9.

Fig.12 shows a dual-JFET version of the modulated buffer. In this configuration the distortion was greatly improved and I would say this is our first Hi-Fi buffer. It's also small and could be made into an 8-pin DIP module to directly replace IC op amps wired as buffers.

Next month

We will continue our in-depth investigation of high-performance discrete buffers in the next issue.

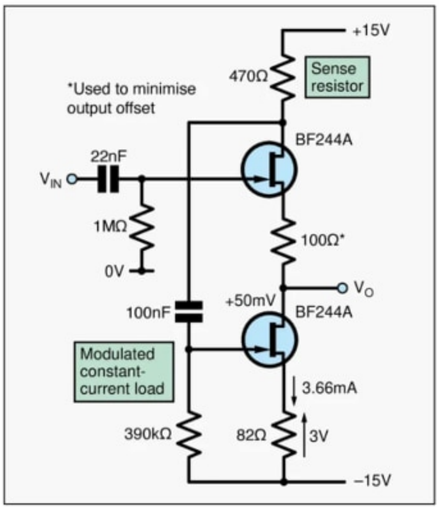

+15V
470Ω
Sense resistor
*Used to minimise output offset
BF244A
22nF
V$_{IN}$
1MΩ
100Ω*
0V
V$_O$
+50mV
BF244A
100nF
Modulated constant-current load
3.66mA
390kΩ
82Ω
3V
–15V

Fig.10. Solid-state version of White follower using two JFETs (which are very similar to triodes). Modulation of current source gives a large distortion reduction down to 0.06%.

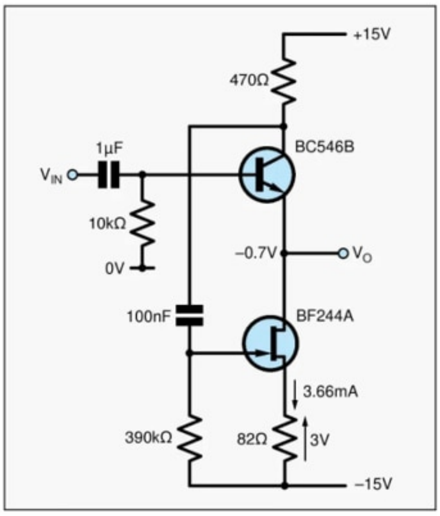

+15V
470Ω
1µF
BC546B
V$_{IN}$
10kΩ
–0.7V
V$_O$
0V
100nF
BF244A
3.66mA
390kΩ
82Ω
3V
–15V

Fig.11. Bi-polar transistor version of White follower. Distortion is about 0.06%.

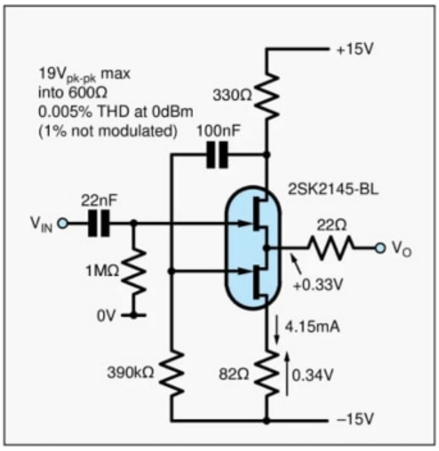

+15V
19V$_{pk-pk}$ max
into 600Ω
0.005% THD at 0dBm
(1% not modulated)
330Ω
100nF
2SK2145-BL
22nF
V$_{IN}$
22Ω
V$_O$
1MΩ
+0.33V
0V
4.15mA
390kΩ
82Ω
0.34V
–15V

Fig.12. Dual matched-pair JFET modulated buffer. It has an impressive THD figure of just 0.006%.

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J175, J176, J112, J111, 2N3820, 2N5467, BF244, 2N5460, J230	**£0.60**

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Note '10/63' denotes '10µF 63V'.

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Suflex 2.5% 10nF/63 (rad. or ax.)	**£0.50**

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330/6.3	**£2.00**
100/35	**£4.00**

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Vigortronix 600Ω VTX-101-3002	**£15**
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A13	**£2.00**
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Potentiometers

Bourns 81

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Bourns 91

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48V PSU (*EPE*, 2019)	**£3.00**
SMT dual transistor adapter	**£0.40**

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Teach-In 2017

Introducing the BBC micro:bit

For Beginners of Any Age

Python Coding on the BBC micro:bit

PYTHON CODING ON THE BBC MICRO:BIT

Jim Gatenby

Python is the leading programming language, easy to learn and widely used by professional programmers. This book uses MicroPython, a version of Python adapted for the BBC Micro:bit.

Among the many topics covered are: main features of the BBC micro:bit including a simulation in a web browser screen; various levels of programming languages; Mu Editor for writing, saving and retrieving programs, with sample programs and practice exercises; REPL, an interactive program for quickly testing lines of code; scrolling messages, creating and animating images on the micro:bit's LEDs; playing and creating music, sounds and synthesized speech; using the on-board accelerometer to detect movement of the micro:bit on three axes; glossary of computing terms.

This book is written using plain English, avoids technical jargon wherever possible and covers many of the coding instructions and methods which are common to most programming languages. It should be helpful to beginners of any age, whether planning a career in computing or writing code as an enjoyable hobby.

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For Beginners of Any Age

Getting Started with the BBC micro:bit

GETTING STARTED WITH THE BBC MICRO:BIT

Mike Tooley

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Mike Tooley's book will show you how the micro:bit can be used in a wide range of applications from simple domestic gadgets to more complex control systems such as those used for lighting, central heating and security applications. Using Microsoft Code Blocks, the book provides a progressive introduction to coding as well as interfacing with sensors and transducers.

Each chapter concludes with a simple practical project that puts into practice what the reader has learned. The featured projects include an electronic direction finder, frost alarm, reaction tester, battery checker, thermostatic controller and a passive infrared (PIR) security alarm.

No previous coding experience is assumed, making this book ideal for complete beginners as well as those with some previous knowledge. Self-test questions are provided at the end of each chapter, together with answers at the end of the book. So whatever your starting point, this book will take you further along the road to developing and coding your own real-world applications.

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Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

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DSP Active Crossover (LCD)	01106196	

PROJECT	CODE	PRICE
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Isolated Serial Link	24107181	£8.50
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Useless Box	08111181	£11.50
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OCTOBER 2019		
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AUGUST 2019		
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PE Theremin (three boards: pitch, volume, VCA)	PETX0819	£19.50
PE Theremin component pack (see p.56, August 2019)	PETY0819	£15.00
JULY 2019		
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MARCH 2019		
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+Processing Board	04101182	£8.60
FEBRUARY 2019		
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NOVEMBER 2018		
Super-7 AM Radio Receiver	06111171	£15.95
OCTOBER 2018		
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	10108162	
SEPTEMBER 2018		
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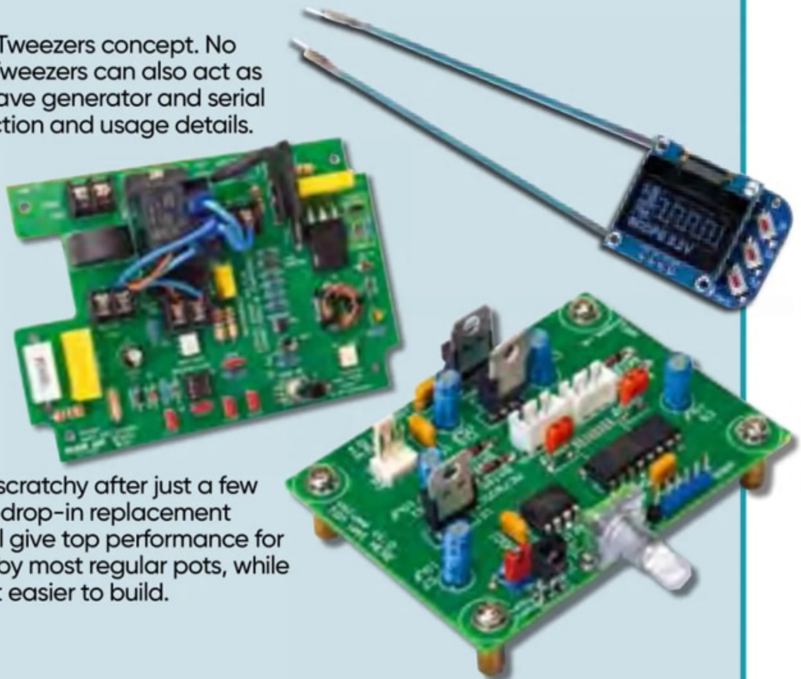
Next Month – in the March issue



Advanced SMD Test Tweezers – Part 2

This new design adds many features to the SMD Test Tweezers concept. No longer only for testing passive components, the new Tweezers can also act as a voltmeter, logic probe, basic oscilloscope, square wave generator and serial protocol analyser. This final article has all the construction and usage details.

Active Mains Soft Starter – Part 2

Our Active Mains Soft Starter is ideal for eliminating the switch-on kick from power tools rated up to 750W. You can also use it to avoid high inrush currents for stationary equipment that can trip circuit breakers or wear out switches. This article covers the assembly, testing, adjustment and calibration of this new Soft Starter.

Digital Volume Control Potentiometer

We got tired of volume control potentiometers going scratchy after just a few years and the very poor balance at low volumes. This drop-in replacement uses a digital IC, so it tracks exceptionally well and will give top performance for decades. The SMD version fits in the space occupied by most regular pots, while the through-hole version does a similar job but is a bit easier to build.

PLUS!

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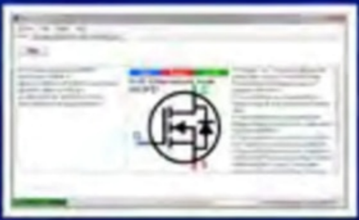

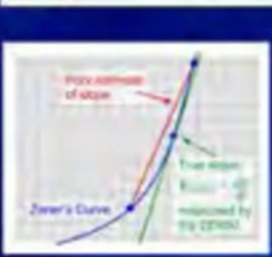

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